Master's Thesis

Changes in Static and Dynamic Stability after Riding an E-scooter

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(Human Factors Engineering)

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ABSTRACT

The electric kick scooter (e-scooter) is a useful personal mobility device for commuting short distances in an urban environment. As sharing services spread worldwide, e-scooters are growing in popularity. Meanwhile, with insufficient institutional adoption and regulations, the rapid spread of personal mobility has raised various safety, political and regulatory issues. Moreover, ergonomic and physiological impacts induced by e-scooter riding must be addressed. The small wheels do not sufficiently absorb vibrations generated while riding, which are transmitted through the footrest and handle to the body, causing whole-body vibration (WBV). This is known to negatively influence the balance sensory system, which leads to postural instability while standing and walking. Additionally, vibration is regarded as a major factor of musculoskeletal pain for occupational drivers. Likewise, e-scooter riding could induce postural instability and musculoskeletal pain due WBV effects.

The objectives of the current study are: (1) to investigate whether riding e-scooter alters standing balance and gait performance. Subjective ratings for physical and mental discomfort were evaluated as well to define health risks; and (2) to clarify the magnitude and properties of vertical acceleration aroused while riding depending on riding conditions. Research findings are expected to identify ergonomic risks predicted by e-scooter riding and provide insights for developing design and riding regulations.

The current research conducted two discrete experiments. The main experiment (n=19), using a plantar pressure sensor, measured standing balance with eye closed (15s) and gait performance (2min) before and after riding an e-scooter. Subjective discomforts were evaluated with 100mm VAS. It was also investigated how much rest would be adequate for recovery. Results revealed that standing and walking performance are significantly affected by e-scooter riding. In the standing test, COP velocity, COP path length and medio-lateral sway increases ($p<0.05$), which means that standing balance declines especially in the ML direction. In walking test results, gait speed and timing became faster ($p<0.05$). Alterations in the standing and walking test tended to recover through 3 to 6 minutes rest. After riding an e-scooter, participants also reported mild dizziness, loss of foot sensitivity and pain in their neck and both knees ($p<0.05$).

In the subsequent experiment (n=4), vertical acceleration generated while riding e-scooter was measured using IMU sensors. Sensors were attached to the footrest, handle and rider's both thighs, waist and head. The collected vertical acceleration data was analyzed depending on road roughness and bodyweight conditions. The magnitude and frequency distribution of provoked acceleration was in a considerably high range while riding the e-scooter. The properties showed differences depending on bodyweight or road roughness. The lighter a rider or rougher the road condition, the greater the

magnitude of the vibration. The vibration channeled through the footrest to the rider's body is attenuated while transmitted upward. However, the acceleration was slightly higher at the head compared to the waist, which is consistent result with subjective ratings result.

As previous studies have demonstrated, WBV aroused during e-scooter riding might negatively influence the balance sensory system, which impairs standing balance. Occurrence of sole cutaneous insensitivity is evidence of the inference. In the walking test, speed alteration seems to happen due to the speed adaptation effect. While riding an e-scooter, sustained exposure to rapid optic flow and wind blowing may influence speed recognition and let participants adapt the rapid speed. The effect might have led to faster walking. The combination of postural instability, unfamiliar walking speed and dizziness could lead to a fall risk. Interestingly, physical discomforts of subjective ratings result and measured vertical acceleration showed consistency. Since riders take considerably high WBV, especially in their knees and neck, musculoskeletal risks are concerned.

This is a pioneering study investigated the ergonomic aspects of e-scooter operation. The current study identifies ergonomic risks predicted by e-scooter riding and provides insight for making design and riding regulations. Research findings would be helpful for e-scooter riders, legislators and manufacturers.

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EXPLANATION OF TERMS AND ABBREVIATIONS

e-scooter	Electric kick scooter
BMI	Body mass index
RMS	Root mean squared
WBV	Whole-body vibration
IMU	Inertia measurement unit
COP	Center of pressure
COG	Center of gravity
VAS	Visual Analogue Scale
ML deviation	Medio-lateral deviation
AP deviation	Anterior-posterior deviation
ADT	Adaptation test
US	Unilateral stance
LOS	Limits of stability
FW	Forward
FWRT	Forward, right
RT	Right
BWRT	Backward, right
BW	Backward
BWLT	Backward, left
LT	Left
BWLT	Backward, left
EC	Eye closed
EO	Eye open

1. INTRODUCTION

1.1 Research Background

Personal mobility comprises a class of compact motorised vehicles that do not normally exceed 25 km/h (16 mph). Its usefulness and convenience have made personal mobility increasingly ubiquitous. Electric kick scooters which is known as e-scooters have become especially popular as they are easy to learn and manipulate, light, compact, and ideal for quickly traversing busy urban areas, particularly when used in conjunction with public transport. As many companies such as Lime, Bird, and Beam offer e-scooter sharing services, the mobility has become a widely used and easily accessible means of transportation around the world. (Lime, 2019; PBOT, 2019; NACTO, 2019).

The number of accidents involving personal transportation methods has risen in concert with their popularity. A new study from the US about injuries from e-scooter mishaps (Trivedi et al., 2019), which focused on two emergency departments from Sept. 1, 2017 to Aug. 31, 2018, found that 249 people involved in e-scooter accidents required medical care with one-third of them being transported to hospital by ambulance. The most common accidents noted were falls, collisions with objects and riders getting struck by a moving vehicle or object. Forty percent of the resulting injuries were bone fractures, with head trauma also noted in 31.7% of cases, while 27.7% involved cuts, sprains and bruises. The study also found that only 4.4% of riders were wearing a helmet when their accident occurred. Even though most e-scooter companies recommend people wear a helmet, there seems to be a low compliance with the most basic safety protocols.

According to statistical data from Seoul Metropolitan Fire & Disaster Headquarters (2020), the number of e-scooter related accident cases doubled from 57 in 2018 to 117 in 2019. Of the total accidents, collisions between e-scooters and cars accounted for 25.5%. The rise correlates with the increased supply of e-scooters. The number of sharing e-scooters in Seoul was only 150 two years ago, compared with 16,580 in May, 2020 and the projected 35,850 in the next three months (Seoul Metropolitan Government City Transportation Headquarters, 2020).

Data from Anti-Corruption & Civil Rights Commission reported that the number of complaints has more than quadrupled from 511 in 2018 to 1,951 in 2019 (Korea JoongAng Daily, 2020). Complains are related to improper parking, request for operation control and regulatory modification and report for fault/illegal e-scooter. There is currently no documented regulations or appropriate solution to these issues yet (Anti-Corruption & Civil Rights Commission, 2019). Given the considerable cases of injuries and usage problems worldwide, legislators are in the process of determining how these devices should be classified, regulated, and accommodated during a period of rapid innovation.

Whereas problems with traffic safety and maintenance have been continuously managed, the negative effects of e-scooters in terms of ergonomics have been overlooked. In terms of posture, sustained standing posture make riders exhausted. Its narrow footrest forces riders to take an awkward posture—i.e., positioning one's feet back and forth respectively. Riders cannot help taking twisted posture. As for design, it has no external protective structure, which let riders directly expose to environmental factors (e.g. wind). E-scooters also feature small wheels for convenient portability. However, the small, hard wheels do not sufficiently absorb the vibration and shocks evoked while riding.

Vibration exposure has long been considered a major cause of drivers' stress and health issues (Serrano-Fernández et al., 2019; Bovenzi and Hulshof, 1998; Bovenzi, 2005). While riding an e-scooter, a certain level of vibration occurs between the wheels and the ground. Riders thus endure whole-body vibrations on an unstable footrest. Whole-body vibration (WBV) is a generic term used when vibrations of any frequency are transferred to the human body. Humans are exposed to vibration through a contact surface that is in a mechanical vibrating state. Although its magnitude and effect may vary depending on riding conditions (e.g. velocity, road roughness, postures), the level of random vibration occurring while riding an e-scooter is normally enough to cause body trembling and head nodding. Additionally, it continuously shocks the hands and feet, which are contact surfaces. Such problems are expected to intensify with the increasing consumer demand for miniaturization and lightening of the e-scooter.

Personal mobility has only recently become widespread in our society, so there are currently no studies investigating the phenomena and changes that occur in rider's body by riding e-scooter. As mentioned above, the design structure, riding posture and evoked WBV may negatively influence the rider's body. For the safe riding and development of personal mobility, it is necessary to investigate predicted ergonomic risks and the degree to which vertical acceleration may arise during operation.

1.1.1 Effects of Whole-Body Vibration on Standing Balance

Static balance is the ability to maintain the body in some fixed posture (Bannister R., 1969). Static balance is the ability to maintain postural stability and orientation with centre of mass over the base of support and body at rest (O'Sullivan et al., 2014). The human postural control system receives information from following three sensory systems; somatosensory (muscle, joint, skin and pressure receptors), visual and vestibular systems (Collins and De Luca, 1993). The three sensory systems (somatosensory, visual and vestibular) are known to be negatively influenced by vibration (Kjellberg and Wikstrom, 1985, Cornelius et al., 1994). Although postural stability during standing depends on descending motor commands from the central nervous system, it cannot be achieved without sensitive and accurate feedback from these sensory systems. Any alteration in the physiology of these sensory systems will result in alteration of postural and equilibrium control mechanisms of the body and likely lead to a loss, or disturbance of balance (Mani et al., 2010).

The effects of WBV on the static balance have been widely investigated. Oullier and coworkers (2009) demonstrated that prolonged exposure (2h) to WBV significantly increases COP area of bulldozer drivers ($p<0.05$) after they operated their vehicle. Researchers inferred that this postural instability is owing to involuntary muscle contraction. Indeed, several studies have revealed that after a muscle is vibrated for several seconds (minimum ~30 s), an involuntary contraction of the previously vibrated muscle often occurs and can last for minutes, even hours (Duclos et al. 2007). In addition, muscle fatigue developed by sustained muscle contraction might contribute to postural alteration cannot be ruled out (Adamo et al. 2002; Park and Martin 1993)

Ahuja et al. (2005) investigated the effect of WBV on the postural stability of long-haul freight drivers. The protocol required postural stability testing prior to, and immediately following, each of three driving sessions of 2.5 hours during a single shift. 30 min rest was provided between sessions. Results showed significant ($p<0.05$) RMS AP sway and ML sway within subject's in eyes open ($p<0.05$) In contrary, vibration induced postural instability did not occur in eyes closed standing condition (Figure 1). In the study, deteriorated postural balance seems to be recovered through rest. Another interesting phenomenon was a time dependent sway increases with each driving shift indicating a cumulative effect of vibration on the system over the course of an entire (8.5 hour) work shift.

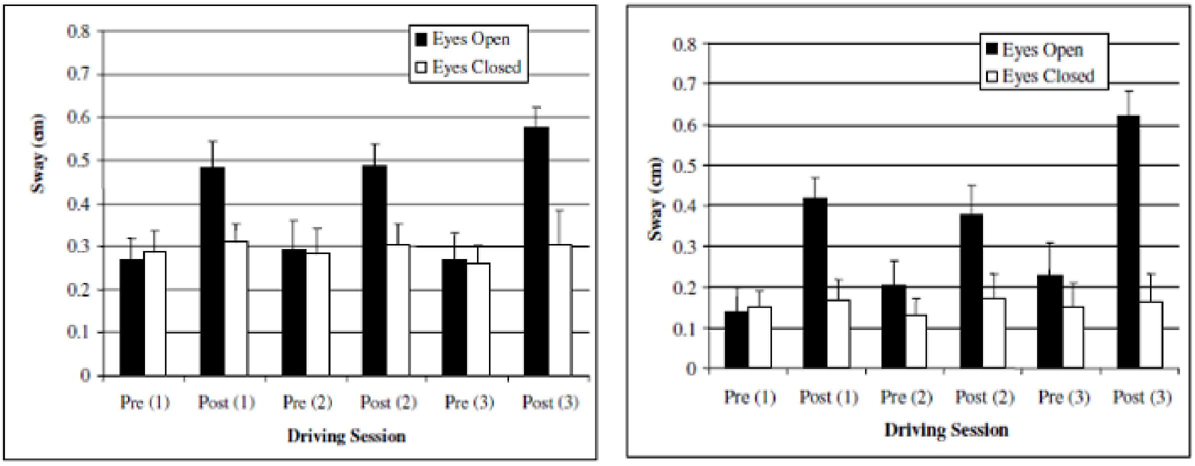


Figure 1. Result of The Study from Ahuja et al. (2005). Left: A/P sway (cm) as a function of eye condition. Right: M/L sway (cm) as a function of eye condition.

Similar results were found in a simulated laboratory study where vibration platform produced vertical vibrations with a fixed, sinusoidal frequency of 18Hz (Martin et al. 1980). After exposure to seated WBV for 30 min, researchers observed a marked enlargement of vertical force amplitude histograms in both ML and AP directions when participants were standing with eye closed.

A review research suggested a possible mechanism concerning how WBV exposure results in balance disturbance (Mani et al., 2010). While exposed to vibration, it is transmitted from the contact area to other distant body part through biodynamic responses (accelerations), which influence the various sensory inputs (visual, vestibular, somatosensory) (Paddan and Griffin, 1998; Dong et al., 2005). Thus, seated WBV is likely to affect the various sub-systems of balance resulting in balance disturbances due to abnormal motor control of the trunk and limbs.

Meanwhile, postural instability is not always observed after vibration exposure. Two laboratory studies reported no decline in standing balance performance on the basis of no significant changes in COP derivatives of; RMS sway, area and velocity (Cornelius et al., 1994) and area, velocity, mean frequency, median power frequency (Santos et al., 2008). Research findings suggest that depending on the properties of vibration (direction, intensity, frequency, etc.) and exposure time, the effect on a standing balance could be varied.

Though considerable studies have demonstrated the effect of WBV exposure on standing balance, they replicated occupational vibration and examined exposure in sitting posture. Vibration properties while riding e-scooter is different from seated WBV in occupational situations. In standing posture, contact area is smaller and vibration transmission tendency might be different compared to seated WBV. Given these properties, it is unknown whether the standing balance deterioration revealed in previous studies would occur even after e-scooter riding.

1.1.2 Effects of Whole-Body Vibration on Fall Risk during Walking

Exposure to WBV increases fall risk. Falls are the second leading cause of accidental or unintentional injury deaths worldwide. There are considerable causes for falls. Among those, the most likely causes are accident/environment-related, gait/balance disorders or weakness, dizziness/vertigo (Rubenstein, 2006). These factors are sufficiently likely to occur even after riding e-scooter.

First of all, e-scooter riders may experience 'gait/balance' problems according to following mechanism. One reason for postural instability after vibration exposure is decline in plantar cutaneous sensitivity. Plantar cutaneous sensation contributes to balance (Meyer et al., 2004). A research revealed that sole sensitivity to touch-pressure and vibration impairs after WBV exposure (Sonza et al., 2013). People who lose plantar sensitivity result in significant reductions in walking speed (Taylor et al., 2004; McDonnell and Warden-Flood, 2000). As sensory information from the foot contributes to the formulation of an egocentric reference frame for balance control (Kavounoudias, 1998), it is likely that subjects adopted a slower walking speed to prevent losing their balance while their feet were insensate.

However, slower gaits have been shown to be directly associated with an increased fall risk (Cromwell and Newton, 2004; Bhatt et al., 2005; Espy et al., 2010). In an experimental research, people who were asked to walk slower than their normal speed showed a large mediolateral COM movement with wider step width (Orendurff et al., 2004). Large lateral sway is vulnerable to fall risk. Therefore, walking at slow speeds may present balance challenges due to increased mediolateral COM motion.

Vibration exposure induces dizziness as well. Although the term dizziness has no specific definition, it is described as some kind of altered orientation in space (Baloh, 1996), a feeling of light headedness or a spinning sensation. Dizziness can be caused by vestibular, cardiovascular abnormality or even psychological state (anxiety, depression) (Matheson et al., 1999) which could be influence by vibration exposure (Mansfield, 2005; Kjellberg and Wikstrom, 1985). Dizziness is one of main factors increasing fall risk (Hall et al., 2010). E-scooter riders may feel dizzy due to sustained WBV exposure and become vulnerable to fall risk.

Given previous research, prolonged WBV provoked by riding e-scooter is possible to distract normal walking increasing fall risk. Thus, it is necessary to investigate whether these alterations happen owing to riding e-scooter.

1.1.3 Vibration Magnitude of Transport and Health Risk Estimation from Its Properties

Vibration has been considered as a factor causing health problems for a long time. Epidemiological studies have revealed the relationship between health risk and long-term, intense vibration exposure. Especially for occupational drivers, exposure to whole body vibration is regarded as one of detrimental factor contributes to musculoskeletal problems (Serrano-Fernández et al., 2019). In a recent review of the long-term effects of WBV on the lumbar spine (Bovenzi & Hulshof, 1999), crane operators, bus drivers, tractor drivers, and fork-lift truck drivers were found to be the most frequently investigated occupational groups. Vibration measurements performed according to ISO 2631-1 showed that vibration magnitude (a_v) varied from 0.25 to 0.67 m/s^2 in cranes, 0.36 to 0.56 m/s^2 in busses, 0.35 to 1.45 m/s^2 in tractors, and 0.79 to 1.04 m/s^2 in fork-lift trucks and freight container tractors. The findings of both cross-sectional and cohort epidemiological studies suggested an increased risk for low back pain (LBP) disorders among occupational groups exposed to WBV when compared to unexposed control groups (Bovenzi, 2005).

Experimental studies measured the vibration occurring while driving and investigated its properties (magnitude, phase, frequency, etc.). From the collected data, they inferred the relationship between vibration and physical pain particularly lumbar pain and spinal risk. Onkunribido et al. (2007) measured vibration at the driver/seat interface using a tri-axial seat pad accelerometer when drivers are driving three different bus in three environmental condition. In Figure 2, the magnitude of vibrations is varied depending on driving conditions (environments, type of bus). Also, using validated questionnaire, information about driving experience, and health history was obtained from 80 city bus drivers. Collected data revealed that drivers feel uncomfortable with vibrations while driving and a large number of drivers are suffering from mild LBP.

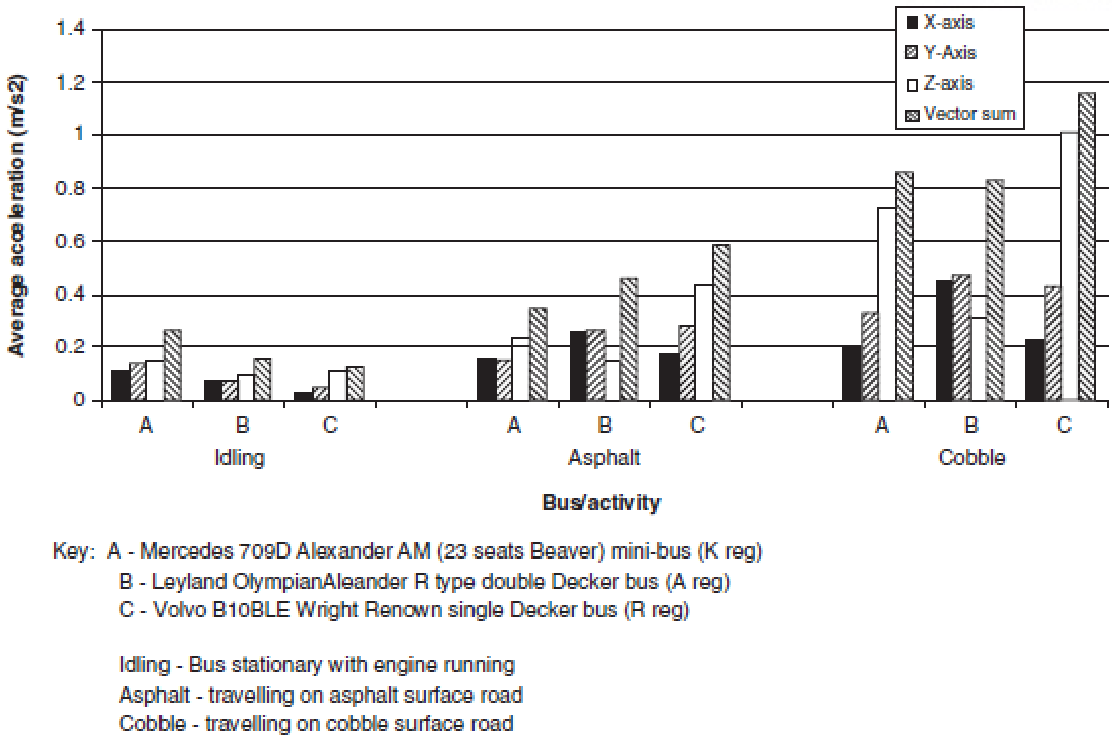


Figure 2. Result of The Study from Onkunribido et al. (2007). The summarized average r.m.s acceleration data for the measured bus vibration.

Considerable individuals also report neck pain due to prolonged WBV exposure while driving (Viikari-Juntura et al., 1994; Rehn et al., 2002; Eger et al., 2008). To explore the relationship, the biodynamic response of seat to head transmission has been extensively studied. Kociolek et al. (2018) measured vibrations using IMU sensors while farmers work on an agriculture quad bike. Sensors were mounted on a seat pad and head. Collected data showed that head RMS is always higher than seat RMS. Amplified and out-of-phase acceleration of the head/neck may explain high prevalence of neck pain in farmers that use quad bikes. Furthermore, to stabilize body disturbing due to WBV, muscle co-activation occurs. Muscle recruitment was important to dynamic equilibrium and stability of the spine, resulting in greater spinal loading. Higher muscle activity may also induce muscle fatigue (Santos et al., 2008),

Biodynamic investigations have shown that the response of the human body to vibration is frequency dependent (Griffin, 1990). The adverse health effects of whole-body vibration can occur in the low frequency range from 0.5 to 80 Hz (Bovenzi, 2005). Resonance frequencies of most human organs and body parts are within the range (Figure 3). When the dominant frequency of WBV corresponds to resonance frequency of human body, the effect is magnified.

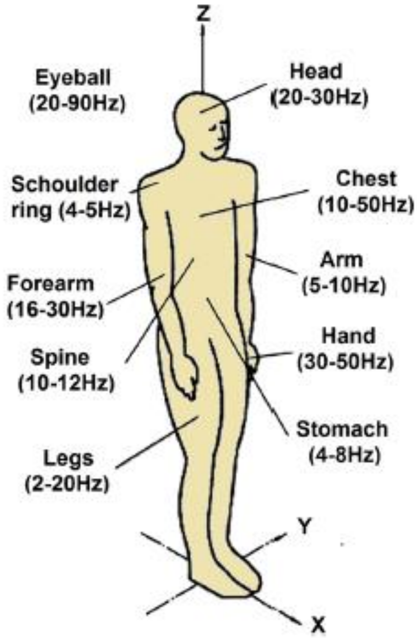


Figure 3. Biomechanical Human Body Model Showing The Resonance Frequencies of Individual Organ (ISO 2631-1, 1997)

As demonstrated in previous studies, sustained vibration exposure is clarified as a causal factor for musculoskeletal risks and its magnitude varies depending on the types of vehicle and road roughness. Research mentioned above have focused on lumbar and cervical pain in seated WBV. However, in the case of standing position, such as riding an e-scooter, feet are directly contacted to the mobility. It supposes that the vibrations transmitted to feet will be particularly great, which would affect distant body part as well such spine structure. Especially, vertical acceleration can amplify compressive load on joint in knees as they bear a large portion of bodyweight.

Unfortunately, there are no research on properties of vibration and how much vibration arises while riding e-scooter. Thus, it is necessary to measure the vibration that occurs when riding an e-scooter and to identify its effects on the human body from its properties and tendency. It is also necessary to find out how these vibrations vary depending on the rider's weight or roughness of the riding ground. By analyzing measured values and comparing them with previous studies, it is expected to estimate what health risks would be developed if users ride e-scooter repeatedly for a long time.

1.2 Research Objectives

Objectives

In summary, although considerable research supports the conclusion that WBV negatively influences standing balance and gait performance, inducing dizziness and other health risks, it is unclear whether similar phenomena would occur even after riding e-scooter. For riders' safety, research on the effects and ergonomic hazards of e-scooter riding is required.

The primary objective of the current study is twofold. First, it investigates whether riding e-scooter alters standing balance and gait performance using a plantar pressure measuring system. To this end, it also evaluated subjective ratings for physical and mental discomfort. Second, it aims to quantify vertical acceleration while riding, factored against the rider's weight and riding surface. With the acceleration data, the properties (e.g., magnitude, frequency, transmission trends) was analyzed. Effects on postural modification and health risks were also inferred. Research findings are expected to suggest insights for developing safe riding guidelines and design regulation for future personal mobility.

Hypothesis

The current study hypothesizes that (1) standing balance would be impaired after riding an e-scooter. In respect to gait, (2) walking balance would decrease, especially in the mediolateral direction, after riding. Walking velocity would become slower as well. Compared to baseline data, (3) dizziness, plantar insensitivity and physical pain in each body part would also occur.

Additionally, it hypothesizes that (4) the properties of measured vertical acceleration would vary depending on riding conditions (e.g., rider's bodyweight and road roughness). Larger vibrations would occur under certain conditions such as a rougher road and a lighter rider. (5) The provoked vibrations while riding e-scooter would be sufficiently severe as to influence the human body system. It is also expected to have properties to support/explain balance alterations and physical discomfort after riding e-scooter.

2. METHOD

2.1 Participants

Nineteen young individuals participated in this experiment. Table 1 presents information of participants. They were screened for musculoskeletal or neurological disorders which might affect their performance. Participants had no problem walking or riding an electronic scooter. People who had an out-toed gait or flat foot were excluded. Using computerized dynamic posturography, it was verified that they have a normal level of postural control capability. Assessment data is described in Appendix A. Before participation, they gave informed consent as approved by the Institutional Review Board.

Table 1. Participants Information. Mean (SD)

	The number of participants	Age, years	Height, m	Weight, kg	BMI, kg/m^2
Total	19	23.74 (2.02)	1.67 (0.09)	60.11 (11.16)	21.33 (2.35)
Male	10	24.70 (2.16)	1.74 (0.05)	69.20 (6.01)	22.82 (1.63)
Female	9	22.67 (1.22)	1.60 (0.06)	50.00 (4.64)	19.67 (1.89)

For acceleration measuring experiment, four healthy participants were recruited (Table 2). Two female participants were categorized into light group and two male participants were heavy group. They met the conditions described above. Additionally, only people who have experienced enough to ride e-scooter naturally without fear were recruited for the experiment.

Table 2. Participants Information 2.

	Subject #	Age, years	Height, m	Weight, kg	BMI, kg/m^2
Light group	1	24	1.61	57	21.99
	2	22	1.63	55	20.7
Heavy group	3	29	1.7	70	24.22
	4	24	1.71	74	25.31

2.2 Instruments

2.2.1 Electric Kick Scooter

Ninebot kick scooter ES2 is used for an experiment. Table 3 describes specifications of the model. Extra battery which is 1.5kg was mounted on it (Figure 4). Maximum speed is technically limited to 15km/h. The Ninebot Kickscooter ES2 was chosen because it is judged to be representative. It has the most similar specifications with the models adopted by many e-scooter sharing services. It is one of most popular models as well.

Table 3. E-scooter (ES2) specification

	ES2	
Dimensions	Length x Width x Height	40x17x45 in (102x43x113 cm)
	Wheel (fore)	8 in (20.32 cm)
	Wheel (rear)	7.5 in (19.05 cm)
Weight	Net	27.6 lbs (12.5kg)
Machine parameters	Max. Speed	15.5 mph (25km/h)
Features	Shock Absorber	Front & rear

Figure 4. E-scooter (ES2) and Extra Battery

2.2.2 IMU Sensor

MTw Awinda (Xsens, Enschede, The Netherlands www.xsens.com) is a wireless human motion tracker. It is small and body-worn inertial measurement sensor (dimension: 47 x 30 x 13 mm, weight: 16g). Each sensor housing a 3-dimentional gyroscope and tri-axial accelerometer. Gyroscopes measured rotational velocity in roll (medio-lateral, ML), pitch (anterior-posterior, AP) and yaw (axial rotation) planes with a range ± 2000 deg/s. Tri-axial accelerometers measured linear acceleration in vertical, lateral and sagittal directions with range ± 160 m/s^2. Three-dimensional data were collected at 100Hz at each sensor. For facilitating visualization, recording and exportation of data, MT Manager V 4.8.2 (Xsens, Enschede, The Netherland) was used (Figure 5).

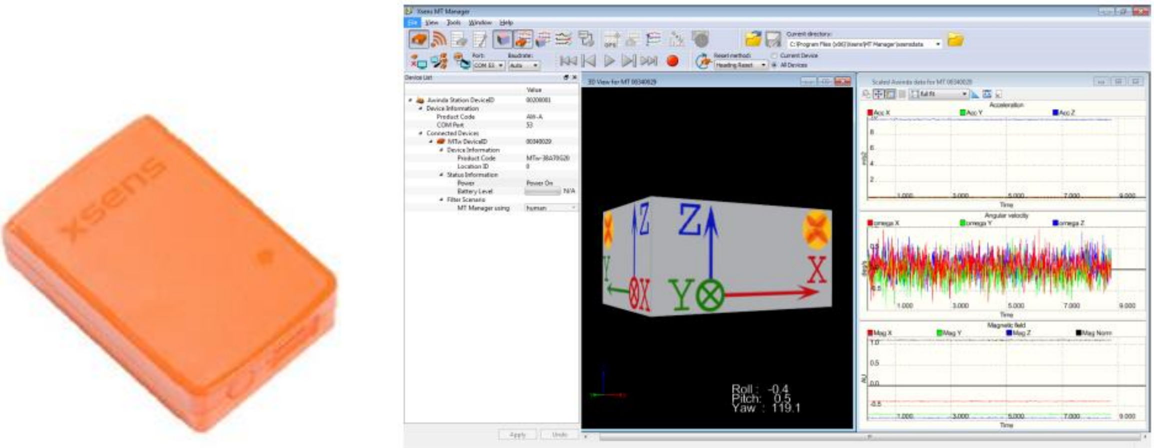


Figure 5. IMU Sensor (XSENS)

2.2.3 Plantar Pressure Measurement System

The Zebris plantar pressure platform (Zebris FDM 1.5; ZEBRIS Medical, Isny, Germany) was used to record plantar pressure in walking or standing posture. The measurement system (158 x 60.5 x 2.5 cm (L x W x H)) had 11264 sensors in sensor area (149 x 54 cm (L x W)). In current research, it was placed in the middle location of 9.1m walkway (Figure 6).

For data acquisition, the Zebris FDM software V1.18.44 (ZEBRIS Medical, Isny, Germany) was utilized. The pressure data were collected at 50 Hz in gait mode, and 60 Hz in stance mode. The software provides the information of stance and gait patterns by analyzing vertical ground reaction force; Spatiotemporal parameters, center of pressure(COP) analysis, force and pressure parameters, and three-foot zone analysis with force, pressure and contact time of forefoot, midfoot and heel.

Figure 6. Plantar Pressure Measurement System (Zebris FDM)

2.2.4 Computerized Dynamic Posturography

Computerized dynamic posturography was used to assess a participants' balancing capability. (SMART EquiTest, NeuroCom, USA). The system provides objective assessment of balance control and postural stability under static or dynamic test conditions. The system provided assessment and retraining capabilities with visual biofeedback on either a stable or unstable support place. The SMART EquiTest utilizes a moveable force plate (46 x 46 x 13 cm (L x W x H)). Force data is collected with sampling rate 100hz. Strain gauges measure the vertical forces exerted by the patient's feet. The device quantifies the force applied by the body to a platform.

Using the Neurocom System software, Version. 8.6.0., clinical balance test was operated and posturographic data from each test is analyzed. The NeuroCom system calculates the position of the COG using the force plate center of force (COF) information along with the participant's height.

2.3. Experimental Design

2.3.1. Experimental Variables

For assessing balance and gait, the riding effect experiment is designed with multivariate variables. Independent variable is 'effect of e-scooter riding' which has four conditions; baseline, immediately after (riding), 3min later and 6min later. Last two conditions mean when measured after taking 3 min rest and 6 min rest respectively. Dependent variables are 'stance parameters' and 'gait parameters', which are described in table 4 and table 5 respectively. Subjective ratings with 100mm visual analogue scale (VAS) which includes dizziness, stress, foot insensitivity, knee pain, lumbar pain, thoracic pain and cervical pain.

In acceleration measuring experiment, independent variables were two factors; bodyweight (lower group, higher group) and road roughness (asphalt, sidewalk). Dependent variable was vertical acceleration measured from rider's body and e-scooter.

Table 4. Description of Stance parameters

Category	Name	Abbreviation	Descriptions
	95% confidence ellipse area (mm^2)	Ellipse	The area containing 95% of all COP samples
	COP path length (mm)	COP length	Measured length of COP path during the analyzed measuring interval
	COP average velocity (mm/s)	COP velocity	Measured average COP velocity during the analyzed measuring interval
	Length of minor axis (mm)		Length of minor axis of 95% confidence ellipse
	Length of major axis (mm)		Length of major axis of 95% confidence ellipse
	Medio-lateral deviation (mm)	ML deviation	The mediolateral displacement deviation of the CoP during the analyzed measuring interval
	Anterior-posterior deviation (mm)	AP deviation	The anteroposterior displacement deviation of the CoP during the analyzed measuring interval
	Forefoot force (%) *		The force of forefoot region
	Backfoot force (%) *		The force of backfoot region

Note. Variable marked with* were measured separately from the right foot and left foot.

Table 5. Description of Gait parameters

Category	Name	Abbreviation	Descriptions
Spatial	Step length (cm) *		The distance between the heel contact of one side of the body and the heel contact of the contralateral side.
parameters	Stride length (cm)		The distance between the heel contract of one side of the body and the heel contact of the same side
	Step width (cm)		The distance between the centers of the feet
Temporal	Step time (sec) *		The duration from the heel contact of side to the heel contact of the contralateral side.
parameters	Stride time (sec)		The duration from the heel contact of one side of the body to the heel contact of the same side
	Cadence (steps/min)		Step frequency
	Walking speed (km/h)		Measured average gait speed during the analyzed measuring interval
CoP butterfly	Length of gait-line (mm) *		Average length of the butterfly diagram during stance phase of one side
diagram	Single support line (mm) *		Average length of the butterfly diagram during single support of one side
parameters	AP position (mm)		Anteroposterior position of CoP intersection point
	AP position sd (mm)		The anteroposterior displacement of the CoP intersection point
	Lateral symmetry (mm)		The mediolateral shift of the CoP intersection point
	Lateral symmetry sd (mm)		The mediolateral displacement of the CoP intersection point
	Max gait-line velocity (cm/sec)		The maximum velocity of butter diagram

Note. Variable marked with* were measured separately from the right foot and left foot.

2.3.2. Procedure for Riding Effect Experiment

A riding effect experiment is comprised of 1-hour two sessions. The first session includes riding task and standing/walking test. The overall procedures summarized in Figure 7. First, baseline data was measured prior to riding the e-scooter. A participant filled in the subjective ratings form (VAS 100mm) about current physical (pain in knee, waist, chest and neck, foot insensitivity) and mental status (dizziness and stress). Details are described in Appendix B. Then, standing test and walking test were followed to collect balance and gait data. Details for two test and task are described in next page.

Test intervention is a riding an e-scooter for fifteen minutes. Sufficient practice and rest were provided before the riding task. Brief tutorial for manipulation and precautions were provided in advance. During break time, riding route, velocity and posture for riding task were instructed. Post to riding task, standing test and walking test were followed immediately. The time lagged from the termination of riding task to standing test (conducted immediately after riding) was less than 30 seconds. Therefore, riding effect would not diminish while conducting test. After two subsequent tests are over, a participant filled in the subjective ratings form again. Rest for three minutes and six minutes later, the identical tests were performed respectively. During rest, participants were asked to sit on a chair comfortably. Excessive movement or stretching was not allowed.

Second session was conducted two to four days later. Individuals visited a laboratory to assess balance capability, which was measured to ensure that recruited participants has a standard level of balancing and to screen out who does not. Standing on Balance master, a participant performed three tests; adaptation test, unilateral stance test, and limits of stability test.

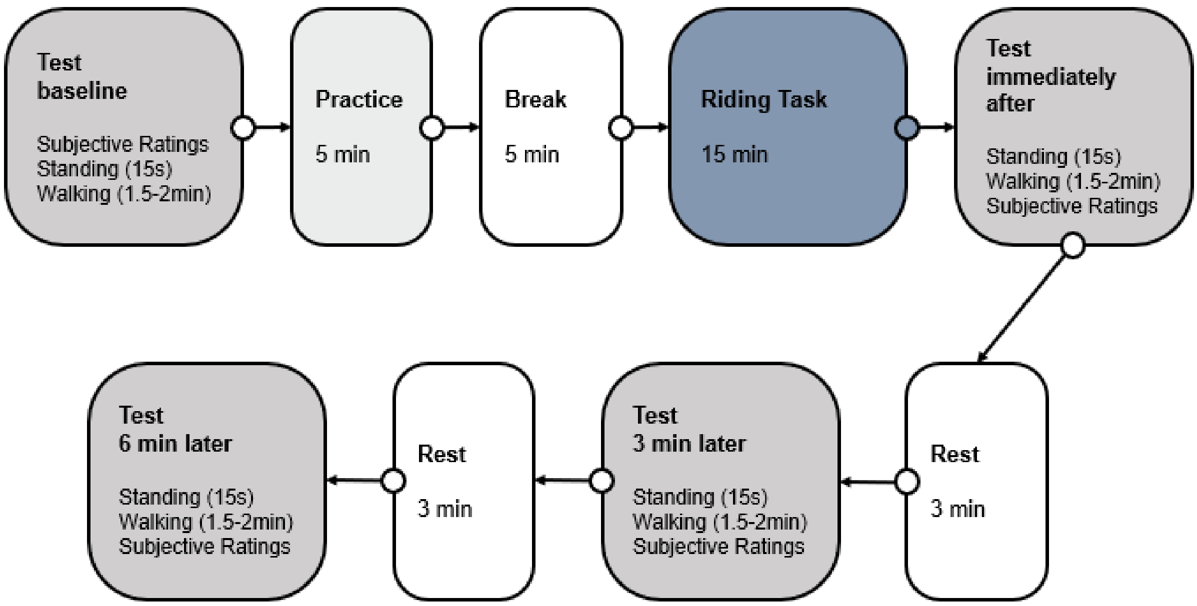


Figure 7. Experimental Protocol

Riding task

Riding task was conducted outdoors. The place is wide enough, less pedestrians, and vehicle-controlled environment. A riding surface was sidewalk which has gaps between blocks. Although the riding route was not specifically controlled, the boundary of riding area was designated (Figure 8, upper).

Before riding, helmet and safety protective guards for elbow, wrist and knee were put on. All the participants put on provided shoes which have thin sole and cushion (Figure 8, left). While riding, participants were asked to ride between 8km/h and 15km/h. The maximum velocity was technically limited to 15km/h. Riding posture was also controlled. One foot is located forward in a straight line and the other was placed behind with slightly external rotated posture (Figure 8, right). Since the footrest area is limited, this posture has been commonly adopted among users. Participants could choose which foot would put forward. They were required to maintain the posture for fifteen minutes. Riding time refers to NACTO (2018) which reported the average riding time for a trip is 15 minutes. It was never allowed to stop riding the electric scooter for fifteen minutes except emergency situations such as accidents, vehicle appearance, and severe pain.

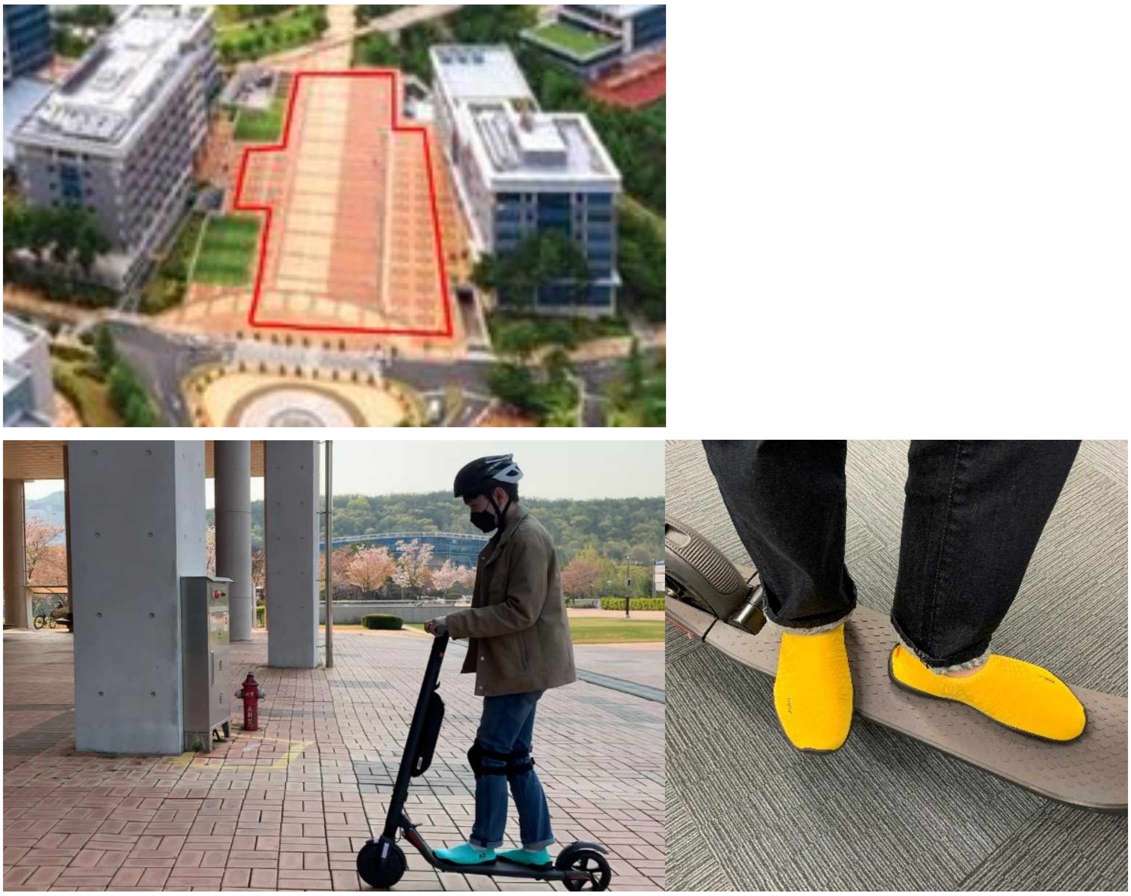


Figure 8. Riding task. (Upper) riding boundary. (Bottom, left) riding posture. upright standing. (Bottom, right) foot position.

Standing and Walking test

Standing test and walking test were conducted indoor. All the participants performed tests four times; baseline, immediately after (riding), 3min later, and 6min later. For standing test, participants stood vertical and horizontal middle of the plantar pressure flatform without shoes, helmet and safety guards. Exceptionally, when standing test right after riding task, participants stood on a platform with knee safety guards for immediate assessment. Participants maintained hip-wide two-legged standing posture with eye closed, head facing straight ahead, and arms at their sides (Figure 9, left). The test lasted 15 seconds.

Subsequently, walking test was conducted. Without shoes, helmet and safety guards, participants walked from an end to the other end along the 9.1m walkway. They were instructed to walk looking forward, maintain natural walking posture and not to turn too fast on the either end of the walkway. Any behaviors which can affect gait pattern such as cough or excessive arm movement were inhibited. Walking test finished at the end of six rounds, which took less than two minutes. (Figure 9, right)

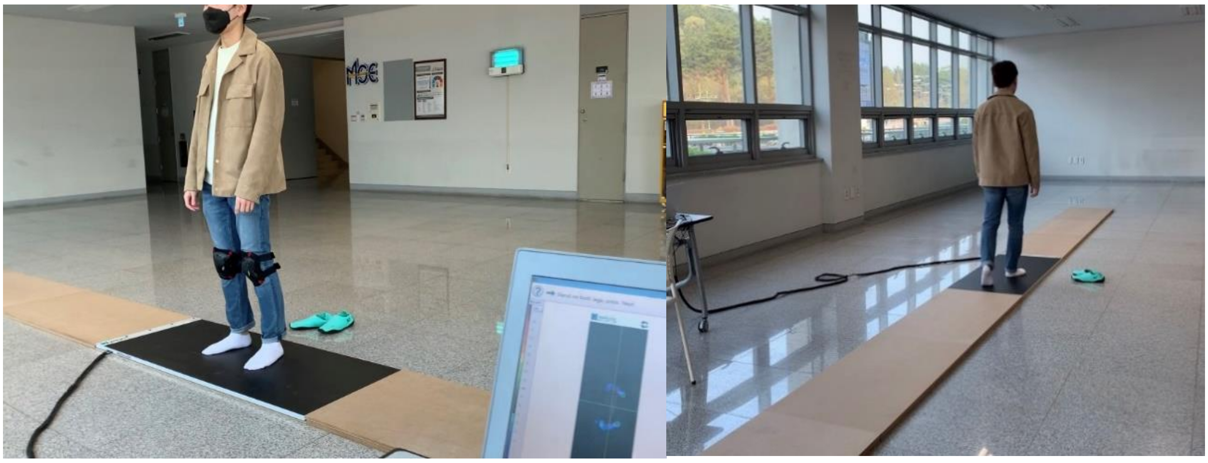


Figure 9. Standing test and Walking test.

Balancing Capability Examination

Participants did light stretching prior to standing on support surface. They wore non-slip socks and safety harness which prevent falling. The harness was connected to frame around Balance master. Standing on a movable, force-sensing support surface, they took three tests (adaptation test, unilateral stance test, limits of stability test). The test order was fixed. Before each test, sufficient exercise to help participants understand how to behave was provided. They took rest more than three minutes between tests.

Adaptation test (ADT)

The ADT assesses the patient's ability to modify motor reactions and minimize sway when the support moves unpredictably in the toes-up or toes-down direction. For each platform rotation, a sway energy score quantifies the magnitude of the force response required to overcome induced postural instability. This adaptive test simulates daily life conditions such as irregular support surfaces. A participant is instructed to keep their eyes opened and to stand still. There will be 5 trials of an 8 degree rotation about the ankle joint for both the 'Toes Up' condition and the 'Toes Down' condition. The test does not get progressively more difficult (i.e. it is the same perturbation every trial). After the end of 5 trials of 'Toes Up' condition, there will be 5 trials of 'Toes Down' condition. The platform moves in the opposite direction, rotating downward. (Figure 10, left)

Unilateral stance (US)

The US is a performance test quantifying the patient's ability to maintain postural stability while standing on one leg for ten seconds with the eyes open or closed. The sequence was as follows: left leg (EO), right leg (EO), left leg (EC) and right leg (EC). Each condition is examined three times. Participants put their hands on their waist during each test. It was not allowed to lean their lifted leg on the supporting leg. The US test provides an objective measure of patient sway velocity for each of the four task conditions (Figure 10, middle).

Limits of stability (LOS)

The LOS is an assessment of the voluntary motor system that quantifies impairments in ability to intentionally displace the COG to the patient's stability limits without losing balance. The patient performs the task while viewing a real-time display of their COG position in relation to targets placed at the center of the base of support and at the stability limits. For each of eight directions (Figure 11), the test measures movement reaction time, movement velocity, movement distance, and movement directional control. Participants must sway with their hip, knees or ankle as they want, but that they must keep their feet firmly planted on the ground. If they step with their feet, the trial must be discarded and started over (figure 10, right).

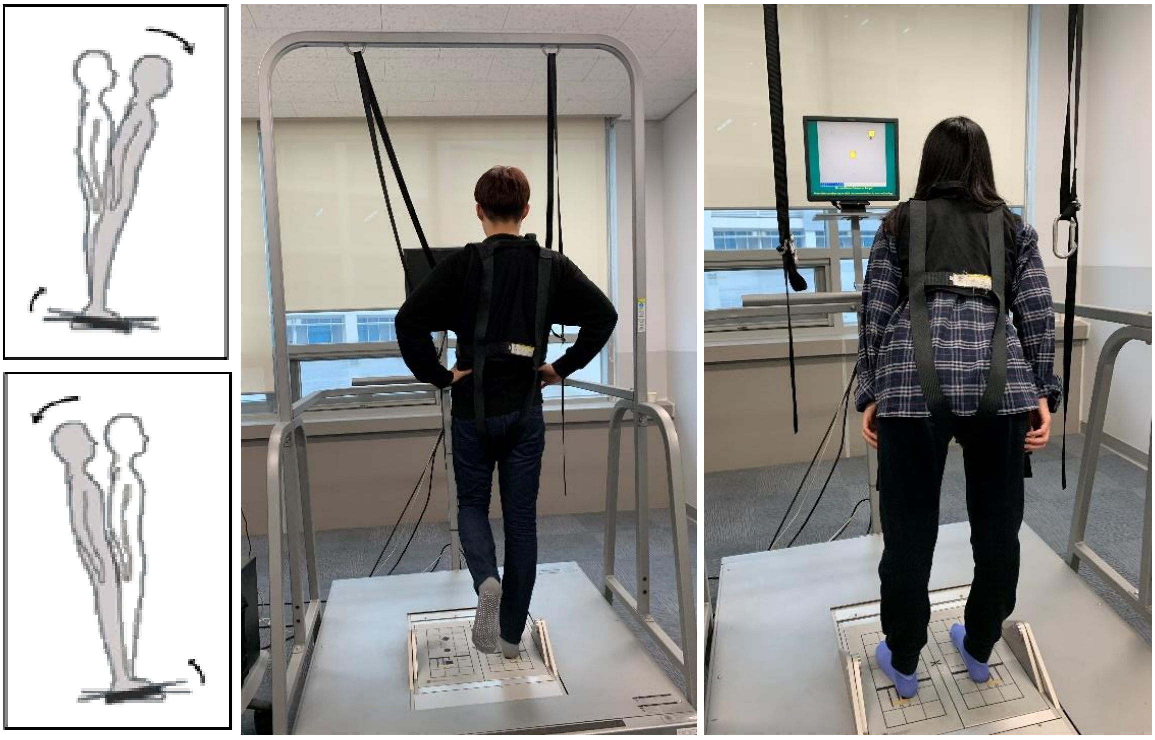


Figure 10. Balance Capacity Examination. (Left) ADT, (Middle) US, (Right) LOS

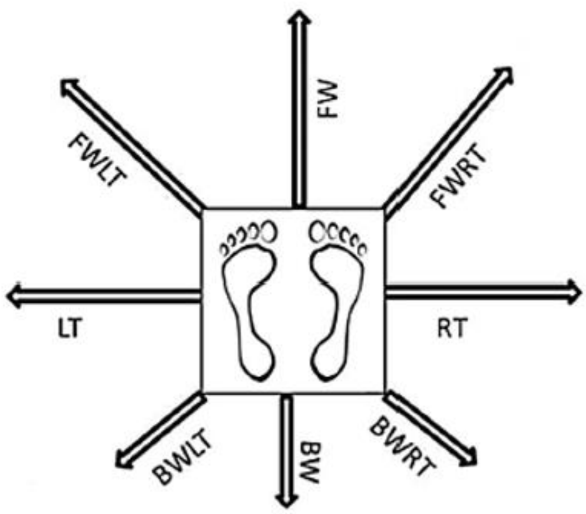


Figure 11. Target Directions of LOS test. FW: forward; FWRT: forward-right; RT: right; BWRT: backward-right; BW: backward; BWLT: backward-left; LT: left; FWLT: forward-left.

2.3.3 Procedure for Acceleration Measuring Experiment

Vertical acceleration while riding an e-scooter is measured using IMU sensors. Sensors are attached on rider's waist near L1 and both thighs anteriorly where 5-10cm higher from knee. Also, a sensor is mounted on head. Two sensors are attached on an e-scooter. One is placed at the center of handle and another is under the footrest (Figure 12).

Participants rode an e-scooter in two road conditions. The two road conditions were asphalt and sidewalk respectively, where the roughness was different. Riding task was conducted in safe environment, where are few pedestrians, vehicle restricted and no other obstacles. The order of the two road conditions was counterbalanced between participants. They conducted a riding task six times in each condition. Riding task in a sidewalk condition was conducted in the same environment with riding effect experiment. Sidewalk is comprised of rectangular blocks and has gaps between blocks.

Participants rode straight for 20-30 seconds according to the start and end cue, maintaining with 10km/h. Since maximum speed was limited to 10km/h technically, all they had to do was just to press the throttle to the maximum. Foot positions, posture and shoes are identical to riding effect experiment (Figure 8). They were all put their left foot at the foreside and right foot at the backward. To rule out noise owing to body movement on acceleration signal quality, they were not to allowed move their head, legs or foot.

Figure 12. IMU Sensor Displacement

Note. IMU sensors attached on participant's head on the top, waist neat L1 and both anterior thighs. Also, two more sensors attached on an e-scooter. At the middle of handle and below a footrest. Data from sensors on thigh is indexed F (fore) and R (rear) not left or right. A thigh of leg placed forward is thigh (F).

2.4. Data processing and Statistical analysis

The collected data from standing/walking test and subjective ratings were analyzed using Matlab R2020a (Mathworks Inc., Natick, USA) and R-Studio Version 1.1.463 (RStudio, Inc, USA). Owing to technical issue, two male participants' walking data measured after taking rest was missed. Thus, only seventeen participants' data were exploited for gait analysis.

To minimize the number of parameters, a paired t-test was performed to analyze the differences between left and right foot. Since there are no significant differences, the measured values of both sides were averaged. Then, one-way repeated measures analysis of variance (ANOVA) was used to evaluate the effect of riding an e-scooter and taking a rest on dependent variables (stance parameters, gait parameters, subjective ratings). Individual difference (e.g. subject) was regarded as a random factor.

Tukey's post hoc analysis test was implemented to find means that are significantly different from each other. A significant criterion of $p<0.05$ was used for statistical analyses.

Association between Parameters

Pearson correlation were applied to examine the relationships between stance parameters, gait parameters and subjective parameters. 'immediately after (riding) – baseline' of each parameter was used for correlation analysis. Only parameters which showed significant differences immediately after riding compared to baseline were applied to correlation analysis.

Acceleration data Processing

Current study only focuses on acceleration in vertical axis. The measured acceleration data were analyzed for only the middle 10 seconds of the total measurement time. In that range, it is confirmed that there were no extreme signals or noise. Acceleration data from inertial sensors were sampled at 100hz, gravity-corrected (R. Moe-Nilssen, J.L. Helbostad, 2002) and band-pass filtered using a 4^{th} order Butterworth filter between 0.5-40hz. Root-mean-squared accelerations (m/s^2) in the vertical axis were calculated. Fast Fourier Transforms (FFTs) were applied on filtered acceleration data, which were used to compute accelerations in frequency domain (hz).

3. RESULT

3.1 Vertical Acceleration

Descriptive data for measured vertical acceleration RMS from each participant are presented in Table 6, Figure 13. The properties of measured acceleration vary depending on body weight and riding road roughness. Weight effect was apparent on sensors attached on footrest and handle. The lighter a rider was, the higher the vertical acceleration RMS was measured in both sensors.

All participants experienced twice greater vertical acceleration when riding an e-scooter on sidewalk compared to asphalt. The magnitude of acceleration RMS recorded on sidewalk was ranged 1.6~2.34 m/s^2 at riders' body and it was much higher at an e-scooter. Whereas, while riding on asphalt the magnitude was below half.

Transmission tendency was consistent across two roughness and two weight conditions. In common with all test conditions, measured vertical acceleration from e-scooter body (handle, footrest) was considerably high. Comparably high acceleration RMS from footrest was attenuated while delivered through legs and waist. It was slightly increased at head compared to waist.

Figure 14 illustrates frequency spectrum of measured acceleration for each sensor depending road roughness. When riding an e-scooter on asphalt, high vibration arises between 25-35hz on footrest. The dominant frequency on handle was around 23-28hz and it has higher amplitude compared to other parts (Table 7). The frequency distribution of acceleration measured on head and both thighs showed a similar trend. (Figure 15). It showed a high amplitude above 20 Hz. On the other hand, when riding on sidewalk, high peak occurred at 21.4hz. Acceleration measured at handle, footrest, head and both thighs had dominant frequency between 20-22hz. Only acceleration measured at waist showed inconsistent frequency distribution pattern compared to other body parts (Table 7, Figure 15).

Bodyweight did not affect to frequency spectrum patterns. The factor only made changes in the size of amplitude (Appendix C).

Table 6. Vertical Acceleration Results in RMS (m/s^2).

		head	lumbar	thigh (F)	thigh (R)	footrest	handle
Asphalt condition							
Light group	Sub1	1.168	0.795	0.872	0.948	3.609	3.008
	Sub2	0.819	0.525	0.949	0.848	2.454	2.973
Heavy group	Sub3	0.711	0.574	0.776	0.686	1.539	2.328
	Sub4	1.049	0.551	1.465	1.042	1.327	2.933
Mean (n=4)		0.937	0.611	1.015	0.881	2.232	2.810
SEM		0.104	0.062	0.154	0.076	0.520	0.162
Sidewalk condition							
Light group	Sub1	2.802	1.784	2.077	1.896	3.848	6.726
	Sub2	2.112	1.596	2.352	2.287	4.320	7.598
Heavy group	Sub3	1.874	1.693	1.647	1.890	3.030	5.776
	Sub4	2.164	1.308	3.293	2.299	2.213	6.441
Mean (n=4)		2.238	1.595	2.342	2.093	3.353	6.635
SEM		0.198	0.103	0.349	0.115	0.464	0.377

Note. Each subject data is averaged over six times riding trials. Thigh (F) means thigh of a leg placed forward and thigh (R) means thigh of a leg placed backward.

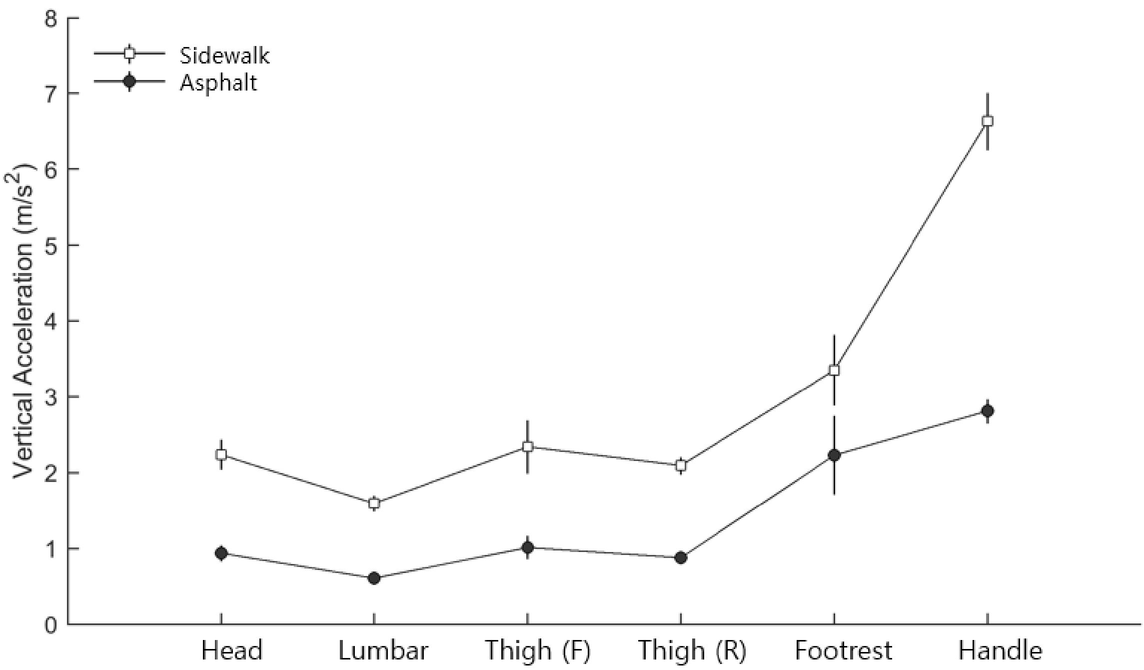
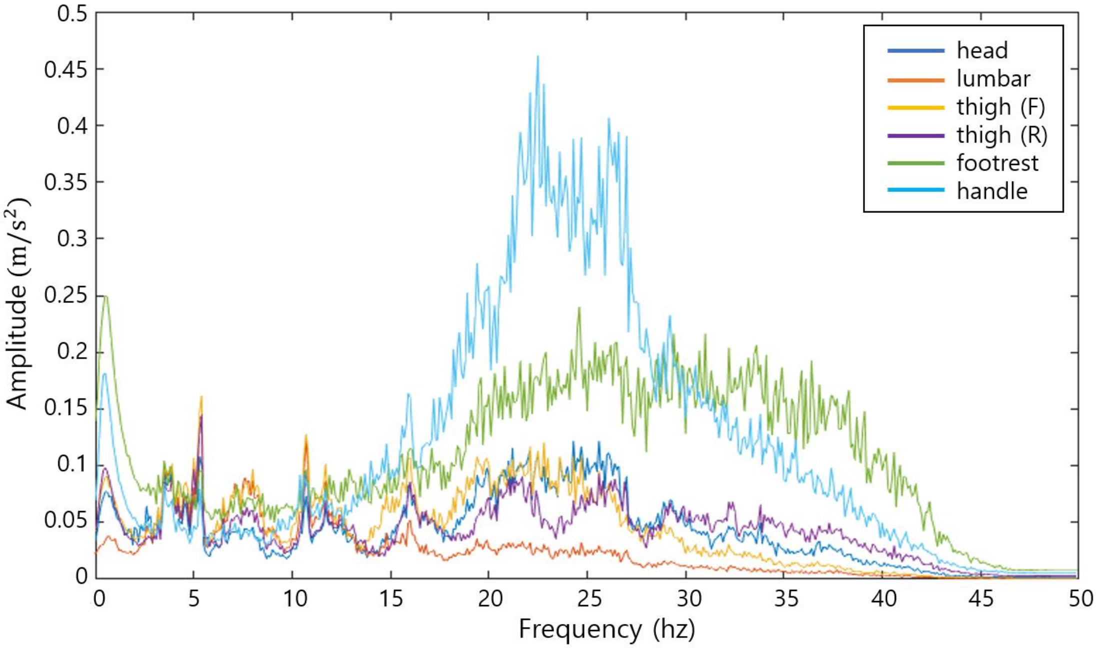


Figure 13. Vertical Acceleration Results in RMS. Mean (SEM) of four participants.



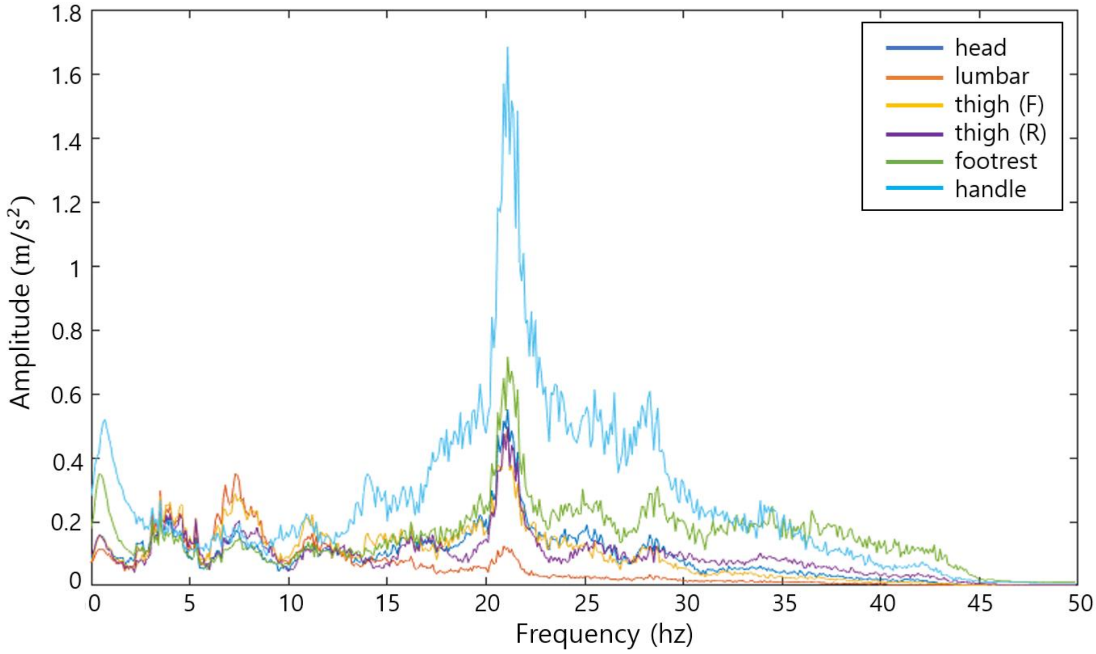


Figure 14. Frequency spectrum. (Upper) asphalt, (Bottom) sidewalk.

Table 7. Frequency Spectrum: Averaged Amplitude at Intervals of 2 Hz. Mean (n=4).

	Asphalt condition						Sidewalk condition					
	Head	lumbar	thigh (F)	thigh (R)	footrest	handle	head	lumbar	thigh (F)	thigh (R)	footrest	handle
0-2	0.055	0.029	0.062	0.062	0.169	0.107	0.108	0.084	0.103	0.101	0.215	0.376
2-4	0.059	0.053	0.057	0.048	0.084	0.053	0.149	0.150	0.138	0.122	0.133	0.202
4-6	0.055	0.065	0.077	0.069	0.072	0.045	0.115	0.147	0.164	0.150	0.107	0.137
6-8	0.038	**0.065**	0.066	0.047	0.064	0.041	0.125	**0.247**	0.211	0.136	0.109	0.154
8-10	0.025	0.046	0.049	0.035	0.063	0.041	0.086	0.148	0.146	0.115	0.086	0.135
10-12	0.044	0.062	0.076	0.049	0.073	0.067	0.099	0.120	0.158	0.092	0.103	0.174
12-14	0.035	0.039	0.044	0.041	0.079	0.066	0.092	0.087	0.108	0.104	0.105	0.195
14-16	0.041	0.031	0.064	0.036	0.086	0.105	0.106	0.077	0.148	0.080	0.131	0.280
16-18	0.052	0.027	0.060	0.053	0.097	0.127	0.131	0.058	0.124	0.131	0.157	0.334
18-20	0.064	0.025	0.084	0.045	0.126	0.212	0.156	0.051	0.168	0.100	0.203	0.494
20-22	0.090	0.028	0.091	**0.074**	0.159	0.285	**0.365**	0.084	**0.309**	**0.317**	**0.479**	**1.107**
22-24	0.091	0.025	**0.094**	0.055	0.172	**0.362**	0.159	0.032	0.153	0.116	0.234	0.656
24-26	**0.100**	0.024	0.080	0.067	**0.187**	0.320	0.156	0.026	0.119	0.113	0.244	0.505
26-28	0.073	0.019	0.054	0.062	0.175	0.298	0.094	0.021	0.080	0.096	0.182	0.458
30-32	0.056	0.013	0.039	0.051	0.173	0.190	0.112	0.023	0.085	0.101	0.236	0.416
32-34	0.040	0.010	0.024	0.051	0.168	0.156	0.053	0.014	0.040	0.080	0.167	0.243
34-36	0.040	0.009	0.022	0.051	0.176	0.126	0.054	0.014	0.038	0.077	0.188	0.200
36-38	0.028	0.007	0.014	0.047	0.154	0.106	0.044	0.012	0.027	0.082	0.187	0.199
38-40	0.026	0.006	0.012	0.041	0.147	0.083	0.034	0.009	0.023	0.059	0.182	0.122

Note. The column at the left end is frequency spectrum from 0 to 40 seperated at intervals of two frequencies. Averaged amplitude in each interval is desctibed. The highest amplitude of each column is marked with bold letter.

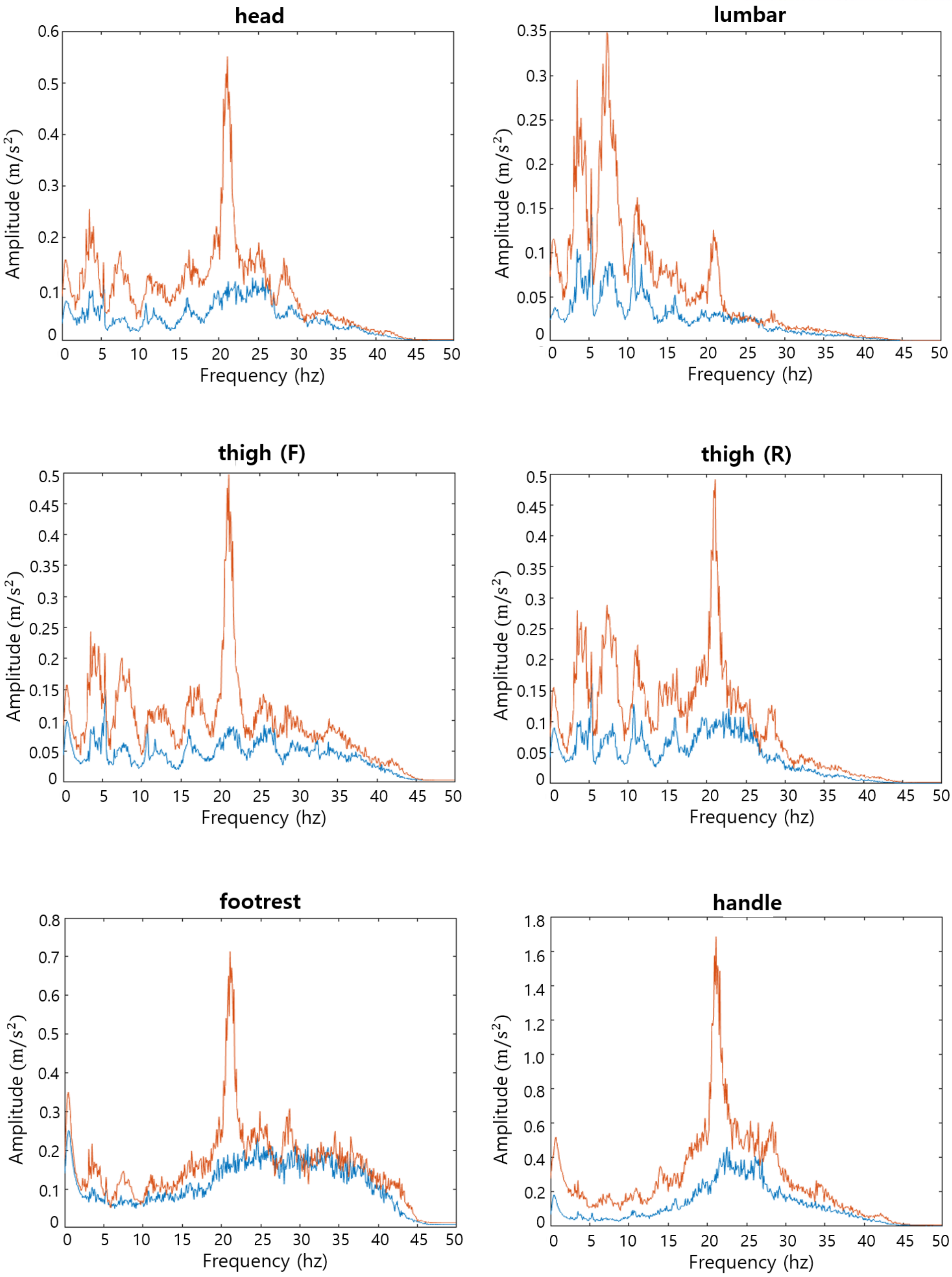


Figure 15. Frequency Spectrum of Each Measuring Position. (Blue) asphalt and (Orange) sidewalk.

3.2 Effects of Riding E-scooter

3.2.1 Stance parameters

A significant decline in standing balance after e-scooter riding was found for measured COP parameters (Table. 8). In Figure 16, COP length (F = 4.497, p<0.01) and COP velocity (F = 4.487, p<0.01) were significantly increased after riding an e-scooter and showed a recovery pattern after taking a rest for six minutes. After riding an e-scooter, length of minor axis (F = 3.874, p <0.05) and ML deviation (F = 3.17, p<0.05) which are indices for lateral sway also increased. Although these two variables were not recovered as much as baseline even with 6 minutes rest, they followed the recovery tendency. Meanwhile, length of major axis and AP deviation which represent sway toward anterior-posterior direction were not affected owing to riding e-scooter (p >0.05). Force distribution of forefoot and backfoot was not different as well depending on conditions (p >0.05).

Table 8. Standing test ANOVA Result

	Baseline	Immediately after	3min later	6min later	F value	P value
Ellipse (mm^2)	115.26 A (12.17)	206.90 A (42.17)	208.08 A (58.49)	158.65 A (24.75)	2.143	0.106
COP length (mm)	105.79 B (8.93)	139.38 A (17.19)	122.82 AB (12.77)	96.90 B (8.53)	4.497	0.00689 **
COP velocity (mm/s)	10.53 B (0.89)	13.88 A (1.71)	12.24 AB (1.27)	9.66 B (0.85)	4.487	0.00696 **
Length of minor axis (mm)	6.72 B (0.60)	9.91 A (1.13)	9.54 A (1.12)	8.93 AB (0.85)	3.874	0.014 *
Length of major axis (mm)	21.71 A (1.61)	24.78 A (2.05)	23.42 A (2.62)	21.12 A (1.94)	0.944	0.426
ML deviation (mm)	1.59 B (0.16)	2.35 A (0.27)	2.16 AB (0.24)	2.17 AB (0.26)	3.17	0.0315 *
AP deviation (mm)	4.32 A (0.34)	4.84 A (0.45)	4.68 A (0.53)	4.08 A (0.39)	0.906	0.444
Forefoot force (%)	43.19 A (1.94)	46.05 A (2.25)	41.19 A (2.37)	43.88 A (2.25)	1.981	0.129
Back foot force (%)	56.81 A (1.94)	53.95 A (2.25)	58.81 A (2.37)	56.12 A (2.55)	1.981	0.129

Note. Mean (SEM), n= 19, *** p < 0.001, ** p < 0.01, * p < 0.05, ‘ p < 0.1, ABC: Tukey’s test category index. One participant’s data was excluded for Fore/Back foot force analysis.

3.2.2 Gait parameters

Means and standard deviations for gait parameters across conditions are presented in Table 9. Step time and stride time which are temporal parameters were significantly reduced ($p<0.001$) after 15 min-riding whereas velocity and cadence were increased ($p<0.001$) (Figure 16). After riding and e-scooter, all participants except one showed increase in their walking speed. It was recovered through rest for three minutes. Although the riding effect on step time, stride time and cadence were lasted more than six minutes, these variables showed a recovery trend through rest as well. Spatial parameters such as step length, stride length and width were not changed.

Length of gait line, AP position, AP position sd, Lateral symmetry, Lateral symmetry sd and Max gait-line velocity representing dynamic walking balance changed slightly after riding e-scooter although there is no statistical significance. These variables are returned to as much as baseline after three minutes rest. However, Butterfly-diagram variables such as AP position, AP position sd, Lateral symmetry, Lateral symmetry sd have not been followed expected recovery tendency when measured after 6 minutes rest.

Table 9. Walking test ANOVA Result

	Baseline	Immediately after	3min later	6min later	F value	P value
Step length (cm)	59.57 A (1.08)	59.90 A (0.93)	59.41 A (1.09)	58.73 A (1.05)	1.601	0.202
Stride length (cm)	119.15 A (2.16)	119.80 A (1.87)	118.83 A (2.18)	117.47 A (2.10)	1.601	0.202
Step width (cm)	10.22 A (0.76)	10.05 A (0.76)	9.78 A (0.75)	10.21 A (0.71)	1	0.401
Step time (s)	0.55 A (0.01)	0.52 C (0.01)	0.54 B (0.01)	0.54 B (0.01)	17.84	6.45e-08 ***
Stride time (s)	1.11 A (0.03)	1.04 C (0.02)	1.07 B (0.02)	1.08 B (0.03)	17.77	6.8e-08 ***
Cadence (steps/min)	109.24 C (2.58)	116.21 A (2.59)	112.98 B (2.44)	112.09 B (2.54)	17.1	1.09e-07 ***
walking Velocity (km/h)	3.89 B (0.10)	4.18 A (0.11)	4.02 B (0.11)	3.94 B (0.11)	9.66	4.24e-05 ***
Length of gait-line (mm)	215.71 A (3.73)	211.46 A (4.29)	212.52 A (3.93)	212.78 A (4.11)	2.291	0.0901
Single support line (mm)	115.38 A (2.59)	113.65 A (2.73)	115.32 A (2.70)	113.84 A (2.54)	1.082	0.366
AP position (mm)	5.35 A (1.25)	4.95 A (1.22)	5.36 A (1.33)	7.69 A (2.18)	2.56	0.0659
AP position sd (mm)	2.08 A (0.31)	2.53 A (0.31)	2.31 A (0.38)	3.41 A (0.84)	1.381	0.26
Lateral symmetry (mm)	2.41 A (0.53)	1.99 A (0.43)	2.5 A (0.58)	3.38 A (1.27)	0.678	0.57
Lateral symmetry sd (mm)	2.52 A (0.27)	2.76 A (0.29)	2.30 A (0.41)	3.72 A (0.80)	1.962	0.132
Max gait-line velocity (cm/sec)	119.56 A (5.91)	131.82 A (5.47)	129.37 A (6.56)	119.70 A (5.11)	2.373	0.0819

Note. Mean (SEM), n=17, *** p < 0.001, ** p < 0.01, * p < 0.05, ‘ p < 0.1, ABC: Tukey’s test category index.

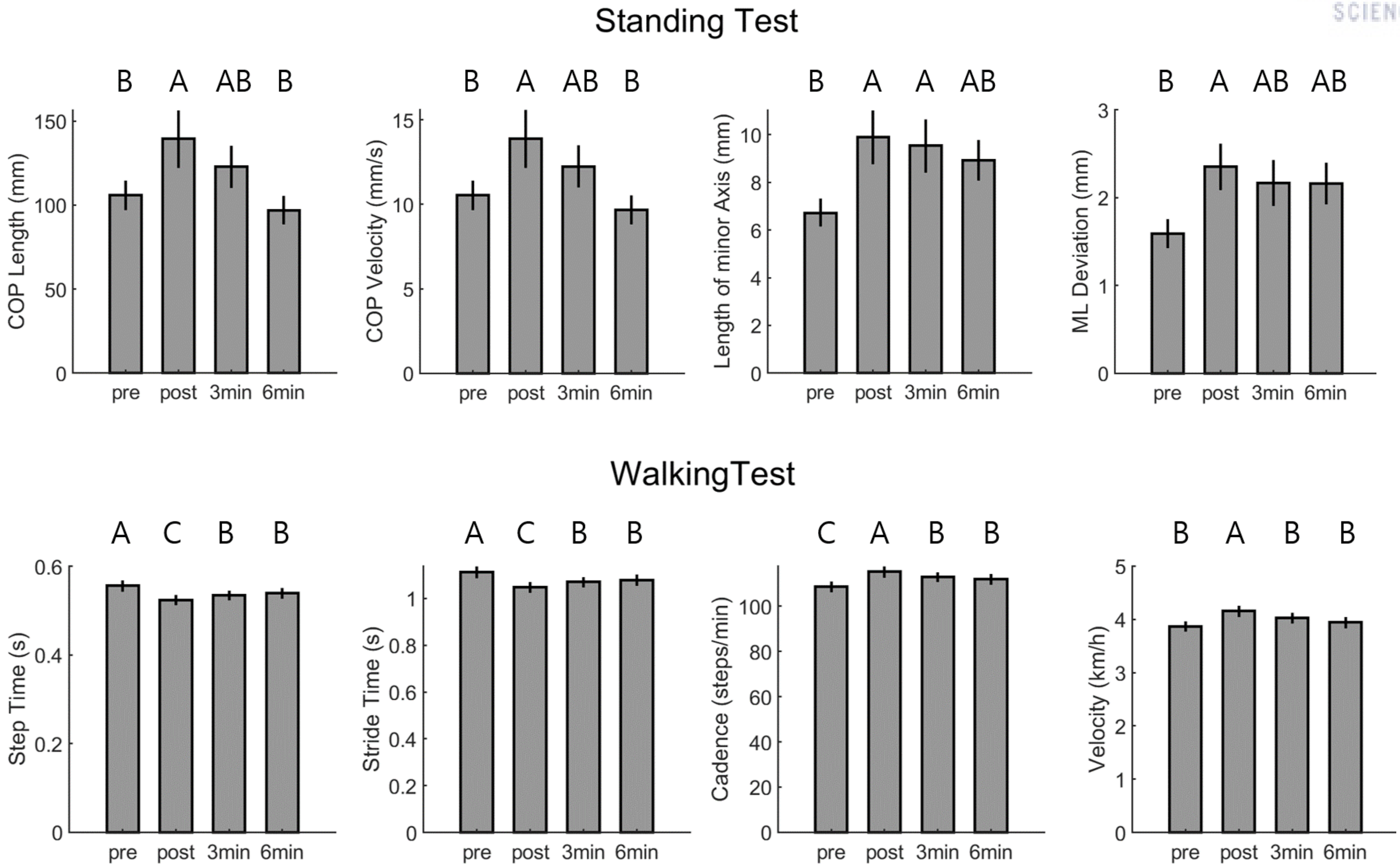


Figure 16. Standing test and Walking test Result. Mean (SEM). n=19 for standing test result and n=17 for walking test result.

Note. ‘Pre’ means baseline data. ‘post’ means data measured immediately after riding. ABC: Tukey’s test category index.

3.2.3 Subjective Ratings

Subjective ratings for discomfort and pain showed significant difference across test conditions (Table 10). Dizziness and foot insensitivity apparently increased after riding an e-scooter and gradually relieved through rest. Participants suffered a pain in both knees placed fore and rear. They reported a mild pain in their cervical spine as well but not in lumbar or thoracic part compared to before riding. In average, a knee placed backward suffer higher pain than the other side. The reported pain in each body part have reduced while taking rest.

Table 10. Subjective ratings ANOVA Result.

	Baseline	Immediately after	3min later	6min later	F value	P value
Dizziness	0.05 C (0.05)	1.63 A (0.39)	0.79 B (0.28)	0.53 BC (0.19)	12.75	2.05e-06 ***
Stress	0.89 A (0.33)	1.26 A (0.37)	0.95 A (0.29)	0.95 A (0.33)	0.559	0.645
Foot insensitivity	0.11 C (0.11)	3.05 A (0.46)	1.32 B (0.28)	0.89 BC (0.20)	28.68	3.15e-11 ***
Knee pain (R)	0.16 B (0.09)	1.16 A (0.37)	0.42 AB (0.12)	0.37 B (0.14)	4.86	0.00495 **
Knee pain (F)	0.26 B (0.21)	0.74 A (0.31)	0.42 AB (0.19)	0.21 B (0.16)	3.585	0.0195 *
Lumbar	0.53 A (0.21)	1.26 A (0.42)	0.63 A (0.23)	0.53 A (0.18)	2.638	0.0588
Thoracic	0.11 A (0.07)	0.42 A (0.19)	0.47 A (0.23)	0.32 A (0.19)	1.019	0.392
Cervical	0.74 B (0.24)	1.53 A (0.39)	0.95 AB (0.27)	0.68 B (0.22)	5.166	0.00327 **

Note. Mean (SEM), n= 19, *** p < 0.001, ** p < 0.01, * p < 0.05, ‘ p < 0.1, ABC: Tukey’s test category index. Knee pain (R) means knee pain from a leg placed rear side. Knee pain (F) means pain knee from a leg placed forward during riding task.

3.2.4 Correlation

Table 11 represents correlation matrix between dependent variables. Only variables with statistical differences ($p<0.05$) between baseline data and data measured immediately after e-scooter riding were used for correlation analysis. There are significant correlations among variables from standing test, walking test and subjective ratings. Walking velocity has moderate level of negative correlation with COP length ($r=-0.458$, $p<0.05$) and COP velocity ($r=-0.459$, $p<0.05$). Foot insensitivity has positive correlation with COP length ($r=0.508$, $p<0.05$) and COP velocity ($r=0.507$, $p<0.05$), whereas it has negative correlation with walking velocity ($r=-0.434$, $p<0.1$).

Table 11. Person Correlation Coefficient Result

	COP length	COP velocity	Length of minor axis	ML Deviation	Step time	Stride time	Cadence	Walking speed	Dizziness	Foot in-sensitivity	Cervical pain	knee pain (R)	knee pain (F)
COP length	1.000	**1.000*****	0.306	-0.184	0.154	0.154	-0.165	**-0.458***	0.042	**0.508***	0.037	0.181	0.217
COP velocity	*<0.001*	1.000	0.305	-0.185	0.154	0.154	-0.165	**-0.459***	0.042	**0.507***	0.038	0.182	0.218
Length of minor axis	*0.203*	*0.204*	1.000	-0.130	-0.086	-0.086	0.129	0.096	0.216	0.025	0.130	-0.231	-0.249
ML Deviation	*0.450*	*0.448*	*0.596*	1.000	-0.369	-0.365	0.113	0.049	-0.127	-0.136	-0.161	0.032	-0.308
Step time	*0.530*	*0.530*	*0.727*	*0.120*	1.000	**1.000*****	**-0.906*****	**-0.577****	0.278	0.280	0.135	-0.078	0.074
Stride time	*0.530*	*0.530*	*0.727*	*0.124*	*<0.001*	1.000	**-0.906*****	**-0.577****	0.276	0.282	0.133	-0.073	0.075
Cadence	*0.501*	*0.501*	*0.600*	*0.646*	*<0.001*	*<0.001*	1.000	**0.761****	-0.305	-0.239	-0.017	0.176	0.081
Walking speed	*0.049*	*0.048*	*0.696*	*0.842*	*<0.01*	*<0.01*	*<0.01*	1.000	-0.313	**-0.434’**	-0.074	0.002	-0.056
Dizziness	*0.864*	*0.864*	*0.374*	*0.604*	*0.249*	*0.253*	*0.204*	*0.192*	1.000	0.371	0.214	-0.183	0.066
Foot insensitivity	*0.026*	*0.027*	*0.919*	*0.580*	*0.246*	*0.241*	*0.324*	*0.064*	*0.118*	1.000	-0.158	**0.582****	**0.556***
Cervical pain	*0.881*	*0.877*	*0.595*	*0.509*	*0.581*	*0.587*	*0.944*	*0.764*	*0.380*	*0.519*	1.000	-0.180	-0.006
knee pain (R)	*0.458*	*0.456*	*0.342*	*0.898*	*0.752*	*0.766*	*0.472*	*0.994*	*0.454*	*0.009*	*0.461*	1.000	**0.865*****
knee pain (F)	*0.373*	*0.370*	*0.305*	*0.200*	*0.764*	*0.760*	*0.741*	*0.820*	*0.790*	*0.013*	*0.982*	<0.001	1.000

Note. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, ‘ $p < 0.1$. Numbers in upper area from diagonal line (left upper to right bottom) is correlation coefficient. Grey area includes correlation coefficient between stance parameters and gait parameters. Yellow area includes correlation coefficient between subjective rating items and stance parameters. Red area includes correlation coefficient between subjective ratings items and gait parameters. Values in bold letters implies two parameters has significant correlation. Numbers in italic type below diagonal line is p-value.

4. DISCUSSION

The rapid increase of e-scooter use has brought political, safety and regulatory problems. The current study focuses on potential physiological and biomechanical issues which riders may experience. A primary objective of the study is to explore whether balance and gait alterations occur after riding e-scooter. Vertical WBV generated during riding is regarded as a factor contributing to alterations. The degree to which vertical acceleration arises while riding and whether it changes depending on riding conditions have been studied. Based on the measured vertical acceleration, its effect on postural alteration (standing, walking) and health risk was inferred as well.

Study results suggest that riding an e-scooter increases postural sway in a user's standing posture and gait speed. Also, participants reported mild dizziness and pain throughout their body parts. The postural instability and subjective discomfort are recovered through rest. Vertical vibration experienced while riding was considerably high in respect to RMS magnitude and frequency range. The properties of vertical acceleration varied depending on riding road roughness and the rider's bodyweight. The current study identifies ergonomic risks predicted by e-scooter riding and provides insight for making design and riding regulations.

4.1. Vertical Acceleration

Vertical acceleration generated while riding an e-scooter is assumed to be a variable negatively influencing on riders' body structure/function. Based on this assumption, the two following research questions arise: (1) How strong is the magnitude of vertical acceleration that occurs while riding and does it change depending on the rider's bodyweight and roughness of the riding environment?; (2) Does the measured acceleration have properties inducing joint stress, muscle fatigue, sensory system degeneration? To answer these questions, vertical acceleration was measured and analyzed into RMS and frequency spectrum.

4.1.1. Road Roughness Effect

The effect of road roughness was distinct on acceleration measured from human body as well as e-scooter. When riding an e-scooter on a sidewalk, the RMS was twice greater than on asphalt—i.e., the rougher the riding surface, the higher the vertical acceleration RMS.

Compared to other methods of transportation, e-scooter riders get relatively severe vertical acceleration on their body. O.O. Okunribido and colleagues (2007) reported that the magnitude of vertical acceleration, measured at the driver/seat interface, ranged between 0.15 and 0.45 m/s^2 during travel on asphalt, while it ranged between 0.3 and 1.01 m/s^2 on cobble surface. In a case of a motorcycle rider, by contrast, the vertical acceleration RMS ranged from 0.88 m/s^2 to 1.18 m/s^2 (Chen et al., 2007). According to ISO 2631-1:1997 standard, the measured acceleration while riding an e-scooter is high enough to induce a feeling of discomfort. (Table 12) In particular, the vibration generated on rough surface (e.g., sidewalk) seems detrimental.

Table 12. Comfort Levels Relate to a_{wz} Threshold Values Proposed by ISO 2631-1 for Public Transport.

a_{wz} values	Comfort level
Less than 0.315 m/s^2	Not uncomfortable
0.315-0.63 m/s^2	A little uncomfortable
0.1-1 m/s^2	Fairly uncomfortable
0.8-1.6 m/s^2	Uncomfortable
1.25-2.5 m/s^2	Very uncomfortable
Greater than 2 m/s^2	Extremely uncomfortable

The spectral analysis result was affected depending on road roughness as well. When riding on asphalt, the dominant frequency was approximately 20-26hz from head, footrest and handle. Meanwhile the range was between 20-22hz from all the measuring parts except waist when riding on sidewalk. The frequency range in both riding conditions is comparably higher than we can usually experience from other methods of transportation. Vibration frequency are dominantly distributed around 1-10hz when driving a car (Kjellberg and Wikstrom, 1985), and 9-14hz when riding on a subway (Lee et al., 2012). It has been suggested that WBV in the frequency range of 0.5 hz to 80 hz may create chronic stresses and possible permanent damage to affected body parts (Hedge 2020). In particular, the observed dominant frequency of the sensor mounted on the head matches its resonant frequency (20–30 Hz). Thus, Head may take severe vibration, leading to vision and hearing discomfort (ISO 2631-1, 1997)

When riding on sidewalk at 10km/h, the measured acceleration had a peak of approximately 21.4hz. Gaps between blocks might be a contributor. Since the vibration property could be changed depending on riding velocity and environmental conditions (e.g., roughness or gaps), the peak will not always emerge within that range.

4.1.2. Body Weight Effect

In both weight groups, $RMS_{footrest}$ and RMS_{handle} were much greater than RMS measured on rider's body (both thighs, waist, head). It suggests that vibration has declined from the e-scooter to distant human body part during transmission. Meanwhile, this attenuation tendency was more distinct in the light group. The heavy group showed lower $RMS_{footrest}$ and RMS_{handle}. Assuming that the heavy weight is loaded on footrest, e-scooters would shake less, causing comparably little vibration to be measured at the footrest and handle. Although light participants showed high $RMS_{footrest}$ and RMS_{handle}, there are no obvious difference in RMS_{thighs}, RMS_{waist}, and RMS_{head} between weight conditions. Given the observed RMS trend, it is assumed that light riders absorbed much vibration through their muscles, joints and tissues in their limbs.

4.2. Effects of Riding E-scooter

The current study primarily focuses on exploring whether e-scooter riding has post-effects on balance and gait pattern. An eye-closed standing test and walking test were conducted before and after a 15-minute riding task. To evaluate postural stability and gait pattern, plantar pressure data was analyzed. Subjective discomfort ratings were collected as well using 100mm VAS. The result was interpreted in relationship with measured vertical acceleration.

4.2.1. Standing Balance

Riding an e-scooter has an acute effect on COP variables (i.e., velocity, path length, lateral sway, lateral deviation), indices for evaluating standing balance. After intervention, postural sway enlarged especially in the medio-lateral direction. On the other hand, the fore/backfoot force did not change, which means they did not leaning forward while standing after a prolonged riding. Maintaining an upright posture for 15 minutes on an e-scooter while exposed to strong airflow and vibration could exhaust the rider. A rider thus might have difficulty with controlling postural stability owing to fatigue. However, the main cause for the observed instability pattern might be whole body vibration induced by the e-scooter riding. Previous research demonstrates a similar pattern, such that standing balance is reduced after experiencing occupational WBV in industries (R, Mani et al., 2010; Oullier et al., 2009; Ahuja et al., 2005; Martin et al., 1980).

E-scooter riders are exposed to considerable random vibration delivered from their hands and feet. It is known that whole-body vibration can influence the various sensory inputs (visual, vestibular, somatosensory) through biodynamic responses (accelerations) of the head, neck and trunk due to well established transmission from contact body parts (Paddan and Griffin, 1998; Dong et al., 2005). Therefore, it is assumed that the sensory systems that control postural stability may deteriorate due to the vertical whole-body vibrations experienced while riding the e-scooter.

WBV or segmental vibration on muscles and tendons has been shown to result in altered proprioception and kinesthetic illusion (Li et al., 2008; Cordo et al., 1995; Roll and Vedel, 1982). Greater muscle co-activation owing to vibration-induced fatigue in concert with inhibited proprioception may increase sensorimotor noise for postural control, delaying response times and negatively influencing corrective movements (Van Dieen et al., 2010). Increased errors in proprioception due to muscle vibration might persist after vibration exposure, possibly due to neuromotor habituation or adaptation (Li et al., 2008; Feldman and Latash, 1982; Wierzbicka et al., 1998). Likewise, while riding on an e-scooter a similar phenomenon is thought to have occurred by WBV delivered from the upper and lower extremities.

In addition, the frequency of measured vibration has properties inducing instability. The dominant frequency was observed between 21-22hz. It has been suggested that balance is impaired at low frequencies (<1 Hz) and frequencies higher than 15 Hz (Kjellberg and Wikstrom, 1985). The RMS_{head} was high enough as well, which suggests that strong head nodding occurred. Strong head-shaking while riding may influence on the sensory systems located within the head and neck (visual, vestibular and neck muscles) regions (R. Mani et al., 2010). Therefore, WBV caused by e-scooter riding could lead to acute sensory function degradation, which finally induces loss of standing balance. According to experiment results after 3 minutes and 6 minutes rest, the sensory degradation seems to have lasted for a time even though a rider stopped riding.

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4.2.2. Walking Balance and Gait Pattern.

Contrary to the hypothesis that participants would walk slowly and lose dynamic walking balance after riding an e-scooter, the opposite changes occurred. Walking test results revealed that participants walked fast. Temporal parameters such as step and stride timing, cadence and velocity changed significantly, which implies the gait cycle became shorter and faster compared to before riding.

One reason for this alteration might be an adaptation to rapid speed. People modify their action based on sensory feedback. That is, people can recognize and modify their walking velocity based on visual feedback and lower extremity somatosensory feedback (Varraine et al., 2002). While riding an e-scooter, participants were instructed to maintain a velocity of 8-15km/h. Fast riding speed causes rapid optic flow and strong airflow.

When a person moves, optic flow happens. It is a global dynamic pattern of apparent motion caused by the relative motion between a moving observer and an environmental scene (Gibson, 1950; Warren, Morris, & Kalish, 1988). Optic flow plays a role in the control of walking speed and navigation through space (Ludwig et al., 2018; Warren et al., 2001; Pechtl, et al., 2020). An incongruity between optic flow information and somatosensory feedback from lower extremities causes people to modify their walking pattern—e.g., walking speed slows when flow velocity is increased and vice versa (Ludwig et al., 2018; Konczak et al., 1994; Pechtl, et al., 2020). In addition, recent studies on gait training with optic flow manipulation for gait velocity improvement suggest that adaptation to modulated optic flow speed can have a post-effect on human locomotion (Kang et al., 2011; Lamontagne et al., 2007).

During riding task, participants continuously exposed to and adapted to fast moving speed. After the end of riding task, when they walk on ground, environmental/sensory feedback may let participants feel their movement velocity is slower than the adapted speed during riding task. Given the feedback, they modified their action (walking) to reach the adapted speed. That is, it is assumed that incongruity between actual speed and expectation and adaptation to rapid speed have cause faster walking. The speed adaptation effect by e-scooter riding lasted even after 6 minutes of rest.

Meanwhile, butterfly-diagram variables representing dynamic walking balance did not significantly deteriorate after riding. One study suggested that vertical and mediolateral COM excursion depends on walking speed. As walking speed increased, the vertical excursion increased, while the mediolateral excursion decreased (Orendurff MS et al., 2004). Therefore, this research supposes that the change in lateral sway was not noticeable due to the fast walking.

4.2.3. Subjective Ratings

Occurrence of plantar sensitivity loss supports the argument that impaired standing balance post-ride owes to proprioceptive sensory degradation. Plantar cutaneous sensation contributes to balance (Meyer et al., 2004), and it is known to be affected by vibration exposure (Sonza et al., 2013). A laboratory study found that after exposure to WBV in standing for 10 minutes, cutaneous sensitivity on the sole declined. WBV influences the discharge of a fast-adapting mechanoreceptor that is sensitive to the rapid application and release of a stimulus (Sonza et al., 2013; Knibestöl et al., 1970). Reduced mechanoreceptor sensitivity would increase the risk of imbalance. That is, vibrations generated by e-scooter riding lead to plantar insensitivity, which seems to cause standing balance loss.

Participants reported mild dizziness after riding. It is assumed that WBV evoked during riding e-scooter may lead to physiological, sensory or psychological dysfunction (Kjellberg and Wikstrom, 1985; Love et al., 1992). Abnormal state of these factors makes people dizzy (Matheson, A. J. et al., 1999). However, the mechanism and main contributor remain unclear.

Subjective discomfort ratings showed a connection with measured RMS tendency. Participants reported knee pain after 15 minutes of riding, which is consistent with what can be inferred from the transmission tendency of measured vertical acceleration. Given the difference in magnitude between $RMS_{footrest}$ and RMS_{thighs}, it is assumed that a large amount of vibration is absorbed from the lower leg. As the vibration is transmitted in upright standing posture with knee extension, compressive load would have been applied to knee, which might induce musculoskeletal damage. Likewise, although subjective ratings item did not include ankle pain, according to the same mechanism as for knee, it is concerned that ankle also will take severe vertical acceleration while riding e-scooter.

In addition, neck pain was more noticeable than in the waist or chest. Measured RMS showed a similar pattern as well, where RMS_{head} was higher than RMS_{waist}. Considering a natural mobility of cervical spine, vertical vibration would have amplified head nodding (A.M. Kociolek et al., 2018). Amplified accelerations at the head/neck may increase compressive load of the cervical spine (Wang et al., 2010), which lead to pain in cervical region. Also, supporting and stabilizing head perturbation requires high co-activation of the neck muscles. Higher muscle activity may induce muscle fatigue. (Santos et al., 2008).

4.2.4 Correlation

The correlation matrix provides a convincing demonstration for association between parameters. (1) Foot insensitivity has a positive correlation with COP length and COP velocity. It implies the greater the insensitivity of the soles was after riding, the greater the COP length and COP velocity were and vice versa. In other words, a participant who felt sole insensitivity greatly after riding showed large deterioration in standing balance. (2) Foot insensitivity has a negative correlation with walking velocity. This relationship means the larger insensitivity become after riding, the smaller was the walking speed increment. (3) Walking velocity showed a negative correlation with COP length and COP velocity. It implies that those who showed larger deterioration in standing balance did not walk faster. Conversely, the less the standing balance deterioration, the larger the walking speed increment.

Loss of plantar cutaneous sensitivity provokes a decline in standing balance (Meyer et al., 2004) and walking speed (Taylor et al., 2004; McDonnell and Warden-Flood, 2000). In the current study, two factors which may affect walking speed are the degree of foot insensitivity and adaptation to rapid speed.

Participants who felt insensitive in their soles greatly after e-scooter riding showed a large reduction in standing balance and little increase in walking speed. It can be inferred that although the adaptation to speed accelerated the pace, its influence is minimized by plantar cutaneous insensitivity.

On the other hand, if there is little sensitivity degradation compared to before riding, standing balance was also little impaired whereas the gait became much faster. In this case, owing to the little effect of plantar cutaneous sensitivity on walking speed, adaptation to rapid speed may dominantly induce walking speed alteration.

4.3. Potential Risks

Fall Risk

Results showed that riding an e-scooter could induce balance disturbance, abnormal walking patterns and dizziness, which are most likely factors leading to a fall accident (Rubenstein, 2006). An e-scooter user may walk toward a destination, cross a crosswalk or even go up and down stairs to take a subway after using it. If they have ridden an e-scooter for quite a long time, the combination of postural instability, unfamiliar fast walking speed and dizziness could lead to a fall accident. Collision with oncoming pedestrians or obstacles may occur as well. Therefore, e-scooter users should keep in mind that postural instability, gait alterations or dizziness could happen owing to riding and behave carefully after end of the ride.

Musculoskeletal Risk

Given the measured vertical WBV and subjective ratings results, standing upright on a strongly vibrating e-scooter seems to have potential musculoskeletal risks, especially in the neck and lower extremities including foot, ankle, calf and knee. WBV exposure and spinal health risk have long been studied. Spine and the internal stress-strain relationship are known to be affected by WBV. Particularly, axial compression in vertical direction could lead to lumbar pain (Seidel, 2005). A review article suggests that occupational seated WBV is related to pathological changes in spine. Besides, vibration did affect joint stiffness and loss of bone elasticity. This is because of the vibration-induced changes in the organization of mineralization (S. Carlsoo, 1982). Therefore, strong vertical WBV evoked while riding an e-scooter can potentially damage vertebral disks in the spine. Furthermore, since the knee is close to the footrest and participants reported significant pain in this part, knee joint stress is also concerned, owing to compressive load by sustained vibration.

It is known that prolonged exposure to vibration with such a magnitude could lead to muscle fatigue and muscle strength reduction (Stewart et al., 2009; Wilder et al., 1982; Mansfiled, 2005). Additionally, due to the direct vibration on the sole and palm, there is a risk of damage to the vascular and neurological systems—e.g., reduced sensory perception and tactile discrimination on hand and foot structure (Mansfiled, 2005).

The predicted musculoskeletal damage is just an assumption derived from experimental results. No cases of musculoskeletal syndrome or chronic pain have been reported yet, as the micro-mobility has a short history and the riding time is shorter than other transportation. However, as sharing services is growing in popularity, e-scooters are spreading rapidly around the world. Although e-scooters are usually used for commuting or leisure, exploiting them as an occupational means of transportation in the near future (e.g., delivery) would increase the riding time and lead to more regular use. Accordingly, attention should be paid to possible musculoskeletal health risks issued by e-scooter riding. A longitudinal study is required to accept personal mobility in our society.

Cognitive Performance

There is concern about cognitive performance as well due to vibration exposure, although this is not investigated in the current study. When riding e-scooters, vertical WBV is high enough to cause dizziness. K. Ljungberg (2007) revealed performance degradation in attention tasks (i.e., search and memory) after exposure to vibrations. N. Costa (2014) found that occupational vibration exposure degenerates cognitive/motor performance. As demonstrated in previous research, the WBV which e-scooter riders experience can influence cognitive performance. Having difficulty to respond quickly, make decisions and judge situations could lead to critical road safety situations.

4.4 Recommendation

The current study figured out postural instability and gait pattern alterations and inferred potential musculoskeletal risks. There are several recommendations to deal with these ergonomic issues.

E-scooter manuals and sharing service instructions should inform that postural instability, dizziness and physical pain could occur after riding it for a certain period of time. It is also recommended to avoid riding continuously for a long time and take a break. Noticing risks is expected to help riders to be careful their behaviors.

It is required to make design regulations to ensure rider's safety. Risks reported in this study would be relieved by better design. For safe riding, e-scooter needs effective shock absorber and wheel which can absorb shock efficiently. Thus, legislator need consider design regulation to reduce vibration. However, it should be examined carefully because price/safety trade off may arise.

Above all, it is strongly recommended to conduct further research. Current study is an early-stage study. Thus, there are several limitations and lack of basis of arguments. With more evidence from further, delicate study, it would be possible to give reliable recommendations for design regulations and riding guidelines. Specific suggestions for further study are described in section 4.5.

4.5 Limitations & Further Study

There are several limitations in current study. First, the experimental conditions did not demonstrate various actual riding conditions. 15 minutes riding task examined only one riding posture and road condition (e.g. sidewalk). In this study, although it was revealed that vibration magnitude could vary depending on road roughness, standing and walking test was followed only after riding e-scooter on sidewalk. As the sidewalk is wobble and rough surface, it may influence investigated test variables significantly. Meanwhile, it is unknown how test variables could be different after riding e-scooter on other road conditions. In additions, participants rode e-scooter for 15 minutes. The duration is decided referred to (NACTO, 2018). However, the average riding duration for one trip vary depending on cities and purposes. As postural stability, gait performance and subjective discomfort evaluation were evaluated before and after 15 min riding task, it is unclear to figure out when the significant difference began to occur. Although it is generally assumed that longer exposure durations lead to a greater magnitude of health effects on the system (Bovenzi, 2009), little is known about threshold exposure dose that will influence or predict balance performance, or how long such an effect can last (Lamis and Wilson, 2008; Li et al., 2008; Martin et al., 1980).

When evaluating the effects of whole-body vibration on man, the following five variables are of major importance: intensity, its variation with time, frequency, direction and duration. Since these variables are influenced by riding conditions (e.g. posture, e-scooter model, velocity, road roughness), the degree of postural instability, gait alterations physical discomfort and required break for recovery would be also affected by riding conditions. In further study, to acquire generalizable results, various riding conditions should be considered in experimental design.

Second limitation is absence of control group. The riding effect experiment was within-subject design. Since it did not include control group against e-scooter riding group, it is unclear why and how the postural instability and physical pain occurred. It is impossible to judge whether the present results are due to prolonged standing, vibration or the fact that most participants were e-scooter beginners. Likewise, how the combinations of rapid optic flow, wind blowing and vestibular function lead to gait alteration remains unclear. In further study, a precise experimental design is required to identify the effects of these factors individually.

Despite these limitations, this study is valuable in that it is pioneering work that has identified the properties of WBV that occur during e-scooter riding and ergonomic risk factors of e-scooter. In future, a longitudinal study is necessary to clarify long-term effect of riding e-scooter on ergonomics risk factors. Also, measuring physiological data would be helpful to explore delicate body responses when riding e-scooter. With the data, it is possible to predict health risks.

5. CONCLUSION

The main goal of this study is to investigate whether riding e-scooter alters standing balance and gait performance. Using plantar pressure measurement platform, changes in static and dynamic stability after riding an e-scooter are figured out. Subjective ratings for physical and mental discomfort were evaluated as well to identify health risks. Current study also aims to clarify the magnitude and properties of vertical acceleration aroused while riding depending on riding conditions (e.g. riders' body weight and road roughness). With the filtered acceleration data, the properties (e.g., magnitude, frequency, transmission trends) and its effect on postural modification were analyzed. Effects on health risk was also inferred.

Study results suggest that riding an e-scooter increases postural sway in a standing posture and gait speed. Also, participants reported mild dizziness and plantar numbness. Standing balance deterioration can be explained by impaired proprioceptive system due to sustained WBV while riding e-scooter. Occurrence of plantar cutaneous insensitivity supports this inference. Sustained vibration exposure on human body induce strength reduction, muscle fatigue and sensory system. Combination of these phenomena make participant difficult to control postural stability and corrective movements. Meanwhile, the walking speed alteration seems to be affected by temporary adaptation effect not by WBV. While riding e-scooter, participants exposed to strong airflow and rapid optic flow. Since they adapted the sense of speed due to environmental effect, the adaptation might have induced participants to walk faster.

Vertical vibration experienced while riding was considerably high in respect to RMS magnitude and frequency range. It might have contributed to postural alterations in standing and walking. The properties of vertical acceleration varied depending on riding conditions. The heavier the bodyweight or the rougher the riding road, the higher the vibration is produced. Vertical acceleration RMS was especially high at head and both thighs. The results explain the subjective ratings results where significant pain reported in neck and both knees after riding e-scooter. Therefore, careful attention is required to prevent musculoskeletal symptoms in these body parts.

This study is valuable in that it is pioneering work, identifying the properties of WBV that occur during e-scooter riding and ergonomic risk factors of e-scooter riding. Overall, e-scooter riding has problematic characteristics (e.g. WBV, exposure to environments, standing posture) inducing safety and health issues. Research findings are expected to suggest insights for developing safe riding guidelines and design regulation for future personal mobility.

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APPENDICES

APPENDIX A

: **Participants' Balancing Capacity Assessment Result**

ADT test result. N=19. Sway energy score. Mean (SD)

	Toes up	Toes down
Mean (SD)	58.38 (11.61)	39.38 (10.87)

US test result. N= 19. deg/sec. Mean (SD)

	Left-EO	Left-EC	Right-EO	Right-EC
Mean (SD)	0.58 (0.14)	1.45 (0.25)	0.62 (0.15)	1.35 (0.24)

LOS test result. N=19. Mean (SD)

	RT (sec)	MVL (deg/sec)	EPE (%)	MXE (%)	DCL (%)
FW	0.58 (0.22)	6.51 (2.57)	74.21 (9.45)	86.58 (10.91)	88.32 (8.59)
FWRT	0.58 (0.20)	8.18 (3.12)	94.68 (9.33)	100.63 (7.34)	77.84 (12.50)
RT	0.56 (0.11)	8.17 (2.89)	80.32 (8.74)	87.37 (9.00)	85.00 (8.33)
BWRT	0.59 (0.22)	5.14 (1.38)	73.47 (14.79)	81.74 (13.49)	70.11 (14.46)
BW	0.57 (0.17)	3.57 (1.42)	52.42 (12.78)	61.26 (14.61)	70.84 (20.08)
BWLT	0.58 (0.18)	5.19 (1.56)	66.74 (19.20)	79.26 (15.14)	58.26 (17.33)
LT	0.61 (0.23)	7.17 (2.86)	79.32 (9.64)	85.37 (7.48)	81.63 (7.03)
BWLT	0.58 (0.19)	7.41 (3.27)	93.16 (10.44)	99.05 (8.71)	82.16 (11.14)

Note. LOS test components: RT: reaction time; MVL: movement velocity; EPE: endpoint excursion; MXE: maximum excursion; DCL: directional control. Directions of the targets are: FW: forward; FWRT: forward-right; RT: right; BWRT: backward-right; BW: backward; BWLT: backward-left; LT: left; FWLT: forward-left.

Appendix B

: Subjective Physical/Mental Discomfort ratings

0: 불편함 없음 (no pain)
2: 경미한 수준의 불편함 (mild)
4: 낮은 수준의 불편함 (uncomfortable, troublesome)
6: 스트레스가 될 만큼의 통증/이상. (distressing, miserable)
8: 심한 수준의 통증/이상 (intense, dreadful, horrible)
10: 견디기 힘든 수준의 극심한 통증/이상 (worst, unbearable)

<3번 문항>
평소와 다름없으면 0.
발바닥 감각이 둔하다고 생각되면 1이상.
통증이나 어떤 이유로 감각을 느끼기 어려우면 10에 가깝게.

1. 현재 느끼는 어지러움의 정도. 어지러움. 혼란스러움.

	0	1	2	3	4	5	6	7	8	9	10	
불편함 없음(no pain)	○	○	○	○	○	○	○	○	○	○	○	더이상 견딜 수 없는 수준의 극심한 통증/ 이상 (worst, unbearable)

2. 현재 느끼는 불만, 짜증, 불안감, 귀찮음, 스트레스의 정도

	0	1	2	3	4	5	6	7	8	9	10	
불편함 없음(no pain)	○	○	○	○	○	○	○	○	○	○	○	더이상 견딜 수 없는 수준의 극심한 통증/ 이상 (worst, unbearable)

3. 현재 느끼는 발바닥 감각의 예민도

	0	1	2	3	4	5	6	7	8	9	10	
평소와 다름없으면 0	○	○	○	○	○	○	○	○	○	○	○	통증이나 어떤 이유로 감각을 느낄 수 없으면 10

4. 오른쪽 무릎의 통증

	0	1	2	3	4	5	6	7	8	9	10	
불편함 없음(no pain)	○	○	○	○	○	○	○	○	○	○	○	더이상 견딜 수 없는 수준의 극심한 통증/ 이상 (worst, unbearable)

5. 왼쪽 무릎의 통증

	0	1	2	3	4	5	6	7	8	9	10	
불편함 없음(no pain)	○	○	○	○	○	○	○	○	○	○	○	더이상 견딜 수 없는 수준의 극심한 통증/ 이상 (worst, unbearable)

6. 허리(요추)의 통증은 어느정도 입니까.

	0	1	2	3	4	5	6	7	8	9	10	
불편함 없음(no pain)	○	○	○	○	○	○	○	○	○	○	○	더이상 견딜 수 없는 수준의 극심한 통증/ 이상 (worst, unbearable)

7. 명치높이 (등, 흉추)의 통증은 어느정도 입니까.

	0	1	2	3	4	5	6	7	8	9	10	
불편함 없음(no pain)	○	○	○	○	○	○	○	○	○	○	○	더이상 견딜 수 없는 수준의 극심한 통증/ 이상 (worst, unbearable)

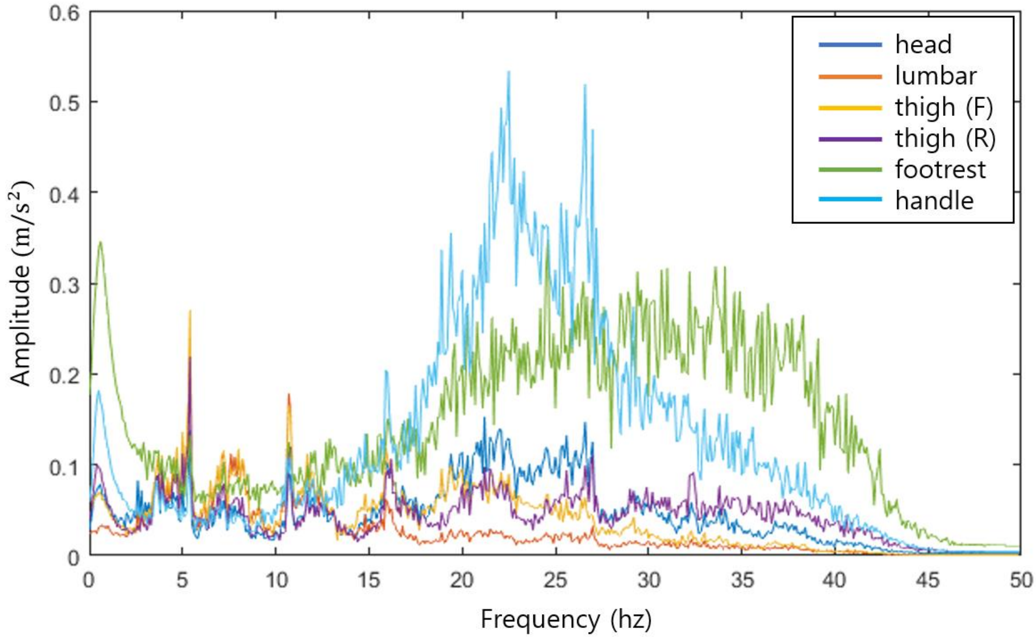
8. 목(경추)의 통증은 어느정도 입니까.

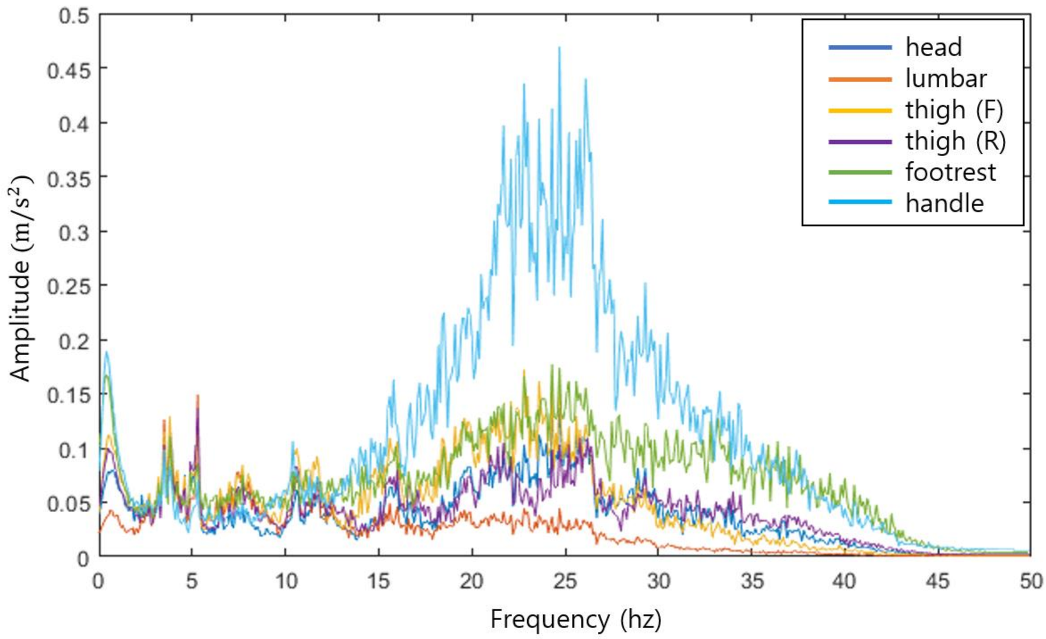
	0	1	2	3	4	5	6	7	8	9	10	
불편함 없음(no pain)	○	○	○	○	○	○	○	○	○	○	○	더이상 견딜 수 없는 수준의 극심한 통증/ 이상 (worst, unbearable)

Appendix C

: Vertical Acceleration Frequency Spectrum depending on Body weight

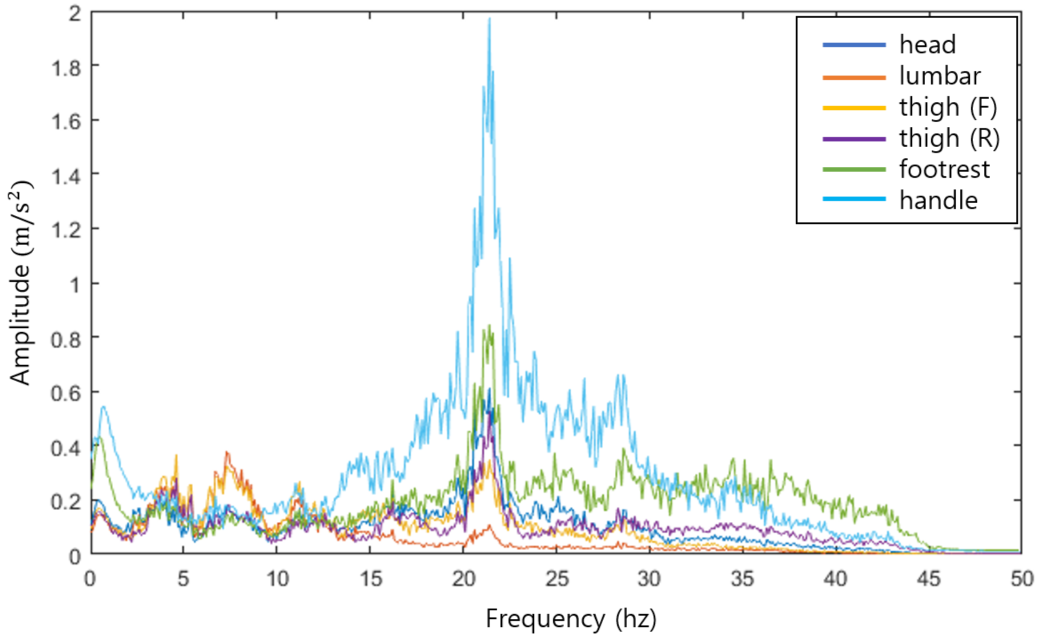
Asphalt condition

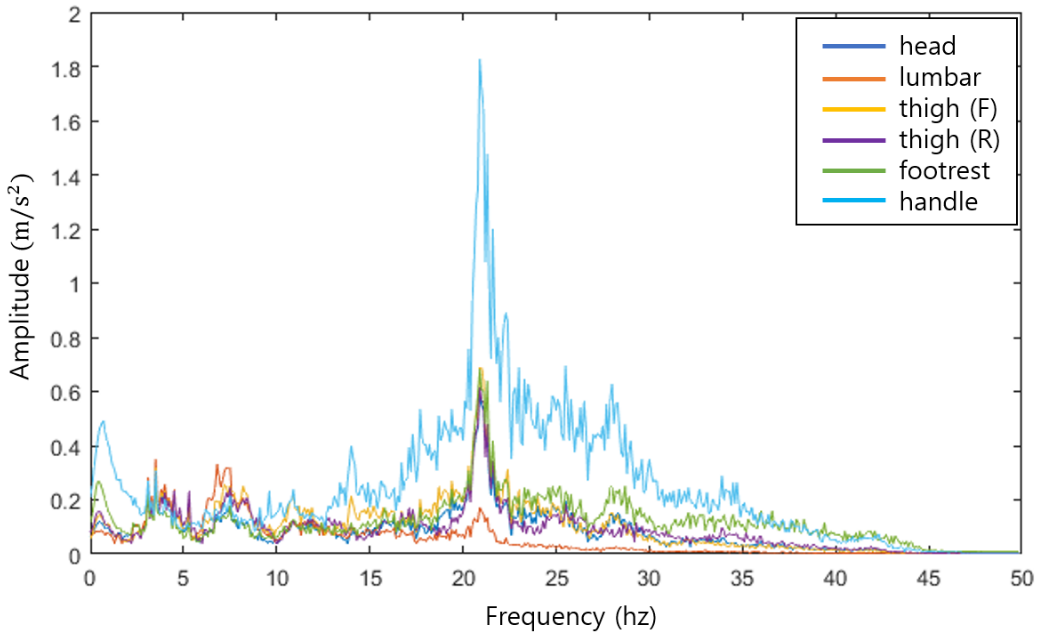




(Upper) frequency spectrum of light group (n=2), (Bottom) frequency spectrum of heavy group (n=2) in asphalt condition.

Sidewalk condition





(Upper) frequency spectrum of light group (n=2), (Bottom) frequency spectrum of heavy group (n=2) in sidewalk condition.

Appendix D

: Full Analysis of Variance Tables

a. Stance parameters

Ellipse

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	112431	37477	2.143	0.106
Participants	18	1093093	60727		
Error	54	944491	17491		
Total	75	2150015	115695		

COP length

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	20180	6727	4.497	0.00689
Participants	18	128126	7118		
Error	54	80782	1496		
Total	75	229088	15341		

COP velocity

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	199.4	66.48	4.487	0.00696
Participants	18	1276	70.89		
Error	54	800.0	14.82		
Total	75	2275.4	152.19		

Length of minor axis

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	116.0	38.68	3.874	0.014
Participants	18	694.5	38.58		
Error	54	539.2	9.98		
Total	75	1349.7	87.24		

Length of major axis

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	157.6	52.54	0.944	0.426
Participants	18	2959	164.4		
Error	54	3006.4	55.67		
Total	75	6123	272.61		

ML deviation

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	6.23	2.0778	3.17	0.0315
Participants	18	41.9	2.328		
Error	54	35.39	0.6554		
Total	75	83.52	5.0612		

AP deviation

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	6.71	2.237	0.906	0.444
Participants	18	123.8	6.875		
Error	54	133.28	2.468		
Total	75	263.79	11.58		

Forefoot force

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	217.4	72.47	1.981	0.129
Participants	17	4549	267.6		
Error	51	1865.9	36.59		
Total	71	6632.3	376.66		

Backfoot force

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	217.4	72.47	1.981	0.129
Participants	17	4549	267.6		
Error	51	1865.9	36.59		
Total	71	6632.3	376.66		

b. Gait parameters

Step length

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	12.3	4.100	1.601	0.202
Participants	16	1055	65.92		
Error	48	123.0	2.561		
Total	67	1190.3	72.581		

Stride length

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	49.2	16.40	1.601	0.202
Participants	16	4219	263.7		
Error	48	491.8	10.25		
Total	67	4760	290.35		

Step width

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	2.13	0.7105	1	0.401
Participants	16	570.1	35.63		
Error	48	34.10	0.7105		
Total	67	606.33	37.051		

Step time

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	0.010506	0.003502	17.84	< 0.001
Participants	16	0.169	0.01056		
Error	48	0.009421	0.000196		
Total	67	0.188927	0.014258		

Stride time

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	0.04187	0.013958	17.77	< 0.001
Participants	16	0.6759	0.04224		
Error	48	0.03771	0.000786		
Total	67	0.75548	0.056984		

Cadence

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	419.7	139.91	17.1	< 0.001
Participants	16	6612	413.2		
Error	48	392.8	8.18		
Total	67	7424.5	561.29		

Walking velocity

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	0.8019	0.26731	9.66	< 0.001
Participants	16	11.89	0.743		
Error	48	1.3282	0.02767		
Total	67	14.0201	1.03798		

Length of gait-line

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	168.4	56.13	2.291	0.0901
Participants	16	16408	1026		
Error	48	1175.9	24.50		
Total	67	17752.3	1106.63		

Single support line

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	43.9	14.62	1.082	0.366
Participants	16	6947	434.2		
Error	48	648.5	13.51		
Total	67	7639.4	462.33		

AP position

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	79.8	26.60	2.56	0.0659
Participants	16	2110	131.8		
Error	48	498.8	10.39		
Total	67	2688.6	168.79		

AP position sd

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	17.31	5.769	1.381	0.26
Participants	16	82.27	5.142		
Error	48	200.53	4.178		
Total	67	300.11	15.089		

Lateral symmetry

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	17.3	5.762	0.678	0.57
Participants	16	248.7	15.54		
Error	48	408.0	8.501		
Total	67	674	29.803		

Lateral symmetry sd

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	19.86	6.619	1.962	0.132
Participants	16	102.1	6.384		
Error	48	161.94	3.374		
Total	67	283.9	16.377		

Max gait-line velocity

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	2096	698.6	2.373	0.0819
Participants	16	22273	1392		
Error	48	14134	294.4		
Total	67	38503	2385		

c. Subjective Discomfort ratings

Dizziness

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	24.99	8.329	12.75	< 0.001
Participants	18	58	3.222		
Error	54	35.26	0.653		
Total	75	118.25	12.204		

Stress

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	1.62	0.5395	0.559	0.645
Participants	18	97.24	5.402		
Error	54	52.13	0.9654		
Total	75	150.99	6.9069		

Foot insensitivity

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	88.47	29.491	28.68	< 0.001
Participants	18	59.11	3.284		
Error	54	55.53	1.028		
Total	75	203.11	33.803		

Knee pain (R)

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	10.84	3.614	4.86	0.00459
Participants	18	19.95	1.108		
Error	54	40.16	0.744		
Total	75	70.95	5.466		

Knee pain (F)

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	3.197	1.0658	3.585	0.0195
Participants	18	55.11	3.061		
Error	54	16.053	0.2973		
Total	75	74.36	4.4241		

Lumbar pain

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	7.16	2.3860	2.638	0.0588
Participants	18	56.74	3.152		
Error	54	48.84	0.9045		
Total	75	112.74	6.4425		

Thoracic pain

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	1.513	0.5044	1.019	0.392
Participants	18	18.53	1.029		
Error	54	26.737	0.4951		
Total	75	46.78	2.0285		

Cervical pain

Source	DF	SS	Mean SS	F-Value	P-Value
Types	3	8.474	2.8246	5.166	0.00327
Participants	18	81.95	4.553		
Error	54	29.526	0.5468		
Total	75	119.95	7.9244		

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